ISLAMIC UNIVERSITY OF TECHNOLOGY
ORGANISATION OF ISLAMIC COOPERATION

Performance Comparison of Microchannel Heat Sink using Nano-Liquid-Metal-Fluid Coolant

A THESIS SUBMITTED TO THE ACADEMIC FACULTY IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

AUTHORED BY,
YASIN KHAN
Student ID: 160011073

MD TANBIR SAROWAR
Student ID: 160011029

MAHIR MOBARRART
Student ID: 160011005

SUPERVISED BY,
PROF. DR. MD. HAMIDUR RAHMAN

DEPARTMENT OF MECHANICAL AND PRODUCTION ENGINEERING

MARCH 2021

CERTIFICATE OF RESEARCH

The thesis titled **"Performance Comparison of Microchannel Heat Sink using Nano-Liquid-Metal-Fluid Coolant"** submitted by Mahir Mobarrat (160011005), Tanbir Sarowar (160011029) and Yasin Khan (16001173) has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering.

Thesis Supervisor

15/03/21

Prof. Dr. Md. Hamidur Rahman
Department of Mechanical and Production Engineering (MPE)
Islamic University of Technology (IUT)

Head of the Department

15/03/2021

Prof. Dr. Md. Anayet Ullah Patwari
Department of Mechanical and Production Engineering (MPE)
Islamic University of Technology (IUT)

DECLARATION

We hereby declare that this thesis titled "**Performance Comparison of Microchannel Heat Sink using Nano-Liquid-Metal-Fluid Coolant**" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Prof. Dr. Md. Hamidur Rahman, MPE, IUT during January 2020 to March 2021.

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

Yasin Khan 15/03/21

Yasin Khan

Student ID: 160011073

15/03/21

Md Tanbir Sarowar

Student ID: 160011029

Mahir Mobarrat 15/03/2021

Mahir Mobarrat

Student ID: 160011005

ACKNOWLEGEMENTS

We would like to express our sincere thanks to our respected supervisor Prof. Dr. Md. Hamidur Rahman sir for his continuous support and guidance throughout this research period and our undergraduate study. His motivation and advice helped us a lot in every step of this research work and writing of this thesis book. His constructive comments helped us a lot to understand and complete this research work.

We are also grateful to our beloved parents for their continuous encouragement and support.

Table of Contents

List of Tables

List of Figures

Nomenclature

MCHS	Micro Channel Heat Sink
Ga	Gallium
GaIn	Gallium-Indium alloy
EGaIn	Gallium-Indium alloy
EGaInSn	Gallium-Indium-Stannum alloy
GaSn	Gallium-Stannum alloy
D_h	Hydraulic diameter, m
W	Width, mm
h	Height, mm
L	Length, mm

Greek Symbol

ρ	Density, m^3/kg
ϑ	Kinematic viscosity, m^2/s
μ	Dynamic viscosity, kg/m-s
φ	Concentration

Subscript

bf	Base fluid
nf	Nano fluid
ch	Channel property
max	Maximum value
min	Minimum value

Dimensionless parameter

Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
f	Friction factor

Abstract

Augmentation of heat transfer from compact areas is a growing concern for many researchers for quite a long time. The search for ultimate cooling solutions is one of the key aspects of transforming different micro-electro-mechanical-systems into compact sizes with heavy computing power. Microchannel heat sink is one of the pioneering cooling solutions available that possess the potential to reach the ultimate cooling solution. In this study, emphasis is given on different coolants used in microchannel heat sinks. The study presents detailed heat transfer and fluid flow analysis in a microchannel heat sink with liquid metal based Nano fluid coolants. The heat transfers and fluid flow inside the micro channels is predicted using finite volume method. The numerical model is validated against experimental data available in literature. The findings in this study is also compared with similar studies available in literature. A good agreement is noticed between present study and the available data in literature. In our study, we've presented for the first time four different solvent materials to prepare the coolant. These solvent materials are gallium based liquid metals which are widely used throughout the world. We've added different Nano particles into these liquid metal solvents to present 'Nano-Liquid-Metal-Fluid' that can remove a larger amount of heat flux compared to the Nano fluids prepared with water.

Chapter 1: Introduction

1.1 Problem statement

During the past three decades, technological advancement led to the rapid miniaturization of manufacturing and electromechanical systems. Miniaturization is considered to be an "economic driver" in recent technological competition and development. Hence it became a rational concern regarding the challenges in the cooling technologies of these devices. Micro and mini-channel compact heat exchangers have become widely popular due to their benefits of reduced dimensions and paving the way for further miniaturization without bringing a compromise in thermal performance.

The bottleneck in cooling technology significantly hampers the rapid development in the miniaturization field of electronic components. Which requires a desperate move, compromising the consideration of economic factors for increasing overall performance. Different scientists took different approaches towards the performance improvements of the heat sinks. The factors associated with the mini/micro-channel heat sink's thermal and hydraulic performance are: channel shape, substrate material, and cooling fluid flow. Various types of mini channel heat sink are available in the market. These include wavy fin microchannel, pin-fin micro-channel, oblique fin microchannel, double-layered micro-channel etc. Still, rectangular cross-section has been considered as the most efficient design accounting economic and machining factor. The substrate material is also limited by the factors associated with material properties for stable heat transfer.

1.2 State of the art

These limitations led to an extensive research on the cooling medium of the heat sink. Liquid metal has been introduced in this field due to its high thermal conductivity. Gallium based liquid metals are chosen due to their excellent thermal conductivity, low viscosity, and non-corrosive properties. However, it comes with a constraint of higher pumping cost. The incorporation of nanoparticle in water also displayed a significant performance enhancement.

These studies opened the door for a new research topic, incorporating Nano-liquid metal fluid as the cooling medium. Ma and Liu [23] proposed the concept of the Nano liquid-metal fluid for the first time, in which the nanoparticles with superior thermal conductivity are added to the liquid metal. Moreover, since liquid metal has large surface tension, a much larger volume fraction of nanoparticles can be added to the liquid metal, so the Nano-liquid-metal-fluid with outstanding thermal conductivity can be obtained. (Zhou *et al.*, 2018) Therefore, the Nano-liquid-metal fluid can be expected to be an idealistic medium for the heat transfer process.

1.3 Procedure

Our study has tried to contribute to this field with a detailed performance comparison of different conventionally used liquid metal and nanoparticle combinations. At first, we validated our numerical mixture model with lee et al.(Lee and Mudawar, 2007) for the water-Al_2O_3 Nano fluid mixture. We have obtained a close accuracy with the reference paper and used this numerical model for further study.

For our comparison study, at first, the thermal and hydraulic performance of different liquid metal-based Nano fluids is compared with that of water using the same Nano particles for the same particle concentration. Effective cooling performance and overall performance also analyzed to obtain the most optimal base fluid in different perspectives. Then, the effect of different nanoparticles is also studied for different base liquid metal fluids for the same particle concentration. This study provides the Nano fluid combination having the highest heat transfer coefficient. Finally, the effect of particle concentration on thermal and hydraulic performance has been studied along with inspection of visual cooling effectiveness and overall performance study.

We have concluded that, GaIn based Nano fluids has displayed the best thermal performance. However, considering the energetic cost of pumping, Ga based Nano fluids displayed the optimal overall performance. In brief, Liquid metal based Nano fluids have considerably higher performance than water-based Nano fluid irrespective of Reynolds number. By comparing the effect of different nanoparticles, CNT displayed better performance than other conventional particles. In the concentration study, it has been found that with concentration increasing, the thermal performance increases. However, the effect of concentration increment decreases for higher particle concentration. The overall performance considering pumping power also shows the same trait. However, with the Reynolds number increasing, the benefit of thermal performance increment decreases.

1.4 Limitations

As our whole work is numerical simulation-based, despite having good consistency and accuracy with the experimental data, we have several limitations. It's very difficult to calculate the exact fin efficiency. Moreover, there is no universal model for the Nano fluid properties prediction. It is also difficult to predict the high-velocity flow in micro channels. Particle agglomeration is also a physical factor that should be taken into account for concentration study.

Our study paves the way for future detailed analysis by providing characteristics of different Nano fluid combinations and optimal range for analysis. Our work has also proposed an effective cooling technique in the field of rapid miniaturization of electronic components by incorporating Nano-liquid-metal fluid as the cooling medium.

Chapter 2: Literature review

In this section extensive literature review has been discussed about the conventional cooling techniques and our proposed Nano-liquid-metal-fluid incorporation in microchannel heat sink.

2.1 Review on Microchannel Heat Sink:

In the last few decades, the process of extraction and dissipation of heat from various kind of Mechanical and Electrical and Electronic devices have got tremendous attention. With the rapid advancement of technology, these concerning devices have become smaller and compact. Along with that, the heat transfer area has shrunk quite drastically so the involvement of conventional heat transfer systems has become minimal and, to some extent incompatible. In the context of these adverse situations, heat dissipation technology has evolved manifold and gives rise to the mini and micro channel heat sink. The concept was first materialized by Tuckerman and Pease (Tuckerman *et al.*, 1981) when they developed the idea of achieving an increased heat transfer coefficient by reducing the hydraulic diameter in the channels. It is evident that the introduction of micro channel heat sink has brought about numerous benefits without compromising the rate of heat transfer (Taylor, 2006; Popescu *et al.*, 2012). Rather it is seen that micro channel heat sink is capable of extracting more heat (1000 W/cm2) (Tuckerman *et al.*, 1981) when compared to the traditional heat sinks (20 W/cm2). The classification has been made to distinguish the micro channel heat sink from the various conventional heat exchangers. The micro channel heat sink application in refrigeration (Kandlikar, 2007) and Air-Conditioning (Han *et al.*, 2012) has been very instrumental. Cooling capacity and Thermal performance of micro channel heat sink was numerically studied for thermal management of electronic devices (Gong, Zhao and Huang, 2015). The numerical and experimental study was conducted on micro channel heat sink (Japar *et al.*, 2018; Naqiuddin *et al.*, 2018). Shape optimization was performed in a micro channel heat sink where it became evident that effect of channel width on thermal performance and pressure drop is very significant (Hadad *et al.*, 2019). Various optimization studies have been carried out where minimum thermal resistance has been considered the design constraint (Weisberg, Bau and Zemel, 1992).

2.2 Review On Conventional Working fluids:

Another important factor in the advancement of heat transfer in micro and mini channel heat sink is the modification and optimization of working fluids. Most of the micro channel heat sink uses water as the working fluid, but there are very few exceptions that include other cooling media associations. Some researchers have considered using freon based refrigerants, but their use has been limited due to environmental impact (Chandra and Prakash, 2016). To overcome certain ecological limitations, the use of eco-friendly has got more attention. Flow Boiling Heat Transfer was investigated in micro channel heat sink using R134a, and it was concluded that heat sink wall temperature could be maintained below 30° Celsius when the mass flow rate is above 1000 kg/m2s with 80W/cm2 heat flux (Li and Jia, 2015). Another comparative study using R123 and R134a in a micro-channel was conducted by Sehwan et al. (In and Jeong, 2009). Few other works include the application of R245fa (Ali, Palm and Maqbool, 2012) and Freon based R141b (Dong *et al.*, 2008) in micro channel heat sink under the same procedure of flow boiling heat transfer. It is evident that the diversified use of working fluid or refrigerant has only been possible in the flow boiling mechanism, and apart from this procedure of heat transfer, the majorly used working fluids are air and water. So, the improvement of these two working fluids has become vital in the advancement of heat transfer in micro channel heat sink, which has been possible by introducing the concept of Nano fluids.

2.3 Review on Nano fluids:

Integration of Nano fluids in the heat transfer space has been an exciting space for research. Nano fluids are made when nanoparticles (typically 1–100 nm in size) that exhibit excellent chemical stability are suspended uniformly in base fluids (Choi, 2009). The selection of nanoparticle is critical because they have to show chemical stability, which leads to the use of stable metals like Cu, Ag, Au or metal oxides, namely titania (TiO2), alumina (Al2O3) and different forms of carbon (diamond, CNT) (Kim *et al.*, 2007). The study of Nano fluids was coined in 1993 by Masuda et al. (Masuda *et al.*, 1993) where the use of Al2O3, SiO2 and TiO2 as nanoparticle with base fluid brought significant change in thermal conductivity and fluid viscosity. Nano fluids have been used in almost all kind of heat exchangers (Huminic and Huminic, 2012). CuO in water (4% volume) has been used as Nano fluid in the flat plate heat exchanger (Pantzali *et al.*, 2009), and in another study Alumina in water and CNT in water was used (Maré *et al.*, 2011) in a flat plate heat exchanger which resulted in 42% and 50% enhancement in convective heat transfer co-efficient for Alumina and CNT respectively when compared against similar parameter of pure water. Al2O3/ethylene glycol [28] and Al2O3/water (volume concentrations 0.3–2%) and TiO2/water (volume concentrations 0.15–0.75%) (Farajollahi, Etemad and Hojjat, 2010) as Nano fluids have been used for heat transfer in Shell and Tube heat exchanger and the result indicated a significant rise in heat transfer characteristics of Nano fluids with Peclet number. An experimental study was conducted on heat transfer enhancement of multi-walled carbon nanotube in a horizontal shell and tube heat exchanger (Lotfi, Rashidi and Amrollahi, 2012). Thermal design of flat tube plain fin compact heat exchanger was investigated using Al2O3/water as Nano fluid and the result shows that pressure drop when 4% of Al2O3 is used is almost double of the base fluid (Vasu, Rama Krishna and Kumar, 2008). Nano fluids have been used to create heating system for the purpose of heating buildings (Kulkarni, Das and Vajjha, 2009). The result shows that the mass flow rate, volumetric flow rate, and pumping power can be reduced to achieve the same heat transfer rate if Nano fluids replace the conventional fluids. They also concluded that the application of Nano fluids had brought a significant size efficiency in the heat transfer system. There are few examples of the application of Nano fluids in heat pipes (Liu and Li, 2012) and vehicle engine cooling system (Sidik, Yazid and Mamat, 2015) where CuO–EG/water and Al2O3–water (Saripella *et al.*, 2007) were used as Nano fluids. All these above studies came to certain common conclusions which are the increase of heat transfer rate, reduction in energy consumption and efficient sizing of heat transfer system.

2.4 Review on the application of Nano fluids in micro and mini channel heat sink:

The introduction of Nano fluids in different heat transfer applications has paved the way for the use of Nano fluids in mini and micro channel heat sinks. Integration of Nano fluids in micro channel heat sink has developed a lot of potential in the heat transfer industry because of their better performance when compared to the prevailing options. Amongst all the possible combination of Nano fluids, the use of Al2O3 has got the maximum attention across all the platform of heat transfer. Forced convective cooling performance was experimentally investigated using Al2O3/Water (1-2% in vol) Nano fluid on micro channel heat sink (Ho, Wei and Li, 2010), and it was evident that there is a very minute increase in friction factor which is very insignificant when compared to the vast reduction in thermal resistance. Heat transfer characteristics were investigated numerically by Kumar et al. (Mukesh Kumar and Arun Kumar, 2020) for electronic chip heat sink where it was found that at volume fractions of 0.25%, 0.5%, and 0.75% of Al2O3/water Nano fluids, the rise in Nusselt number is 9%, 23%, and 37% respectively when compared to water. Wen and Ding (Wen and Ding, 2004) investigated the enhancement of the convective heat transfer coefficient using single phase model using Al2O3/water Nano fluid. CFD modelling on thermal performance of Al2o3/water was studied to compare single and two-phase flow (Moraveji and Ardehali, 2013). It was seen Al2O3/water Nano fluid combination provided the least thermal resistance when compared against a Nano fluid combination of Al2O3 with engine oil, glycerin and ethylene glycol (Alfaryjat *et al.*, 2018). Al2O3 provides better heat transfer performance when compared to SiO2 because of its high thermal conductivity (Alfaryjat *et al.*, 2019). Although Al2O3/Water Nano fluid provided excellent performance in most studies, their long-time usage modifies the crystallite size (Razali, Sadikin and Ibrahim, 2017). As a result, heat transfer performance is affected. So other potential Nano fluids have used in micro channel heat sink for further research purpose. Sivakumar et al. (Sivakumar, Alagumurthi and Senthilvelan, 2017) used CuO as nanoparticle and compared the performance of CuO/water and Al2O3/Water Nano fluids. There are few examples of the use of chemically stable metal as the nanoparticle. Convective heat transfer in a cylindrical micro channel heat sink was studied using Cu/Water Nano fluid where 0.05, 0.1 and 0.3 wt% concentration of nanoparticle was used to enhance the Nusselt number by 17%, 19% and 23% respectively, when compared against pure water (Azizi, Alamdari and Malayeri, 2015). It was found that an increase from 0.05 to 0.3 wt% in mass fraction of Cu nanoparticle resulted in a decrease of thermal resistances up to 21% (Azizi, Alamdari and Malayeri, 2016). Another study on micro channel heat sink was conducted applying Cu–water Nano fluid and using porous media approach and least square method (Hatami and Ganji, 2014). There are few works concerning silver-water Nano fluid in the micro channel heat sink field. It has been studied both experimentally and Numerically (Sarafraz et al. 2018; Yang et al. 2020) As mentioned earlier, different forms of carbon-based Nano fluids have also been studied in micro channel environment. Jang et al (Jang and Choi, 2006) studied the contribution of the diamond (1 vol.%, 2 nm) in water as Nano fluid in microchannel heat sink and concluded that at fixed pumping power, there is a 10% enhancement in cooling performance compared to pure water. Optimization of micro channel heat sink was studied using CNT/Water Nano fluid, where two different kinds of CNT Nano fluids were used (Mohd-Ghazali *et al.*, 2019). The weight concentration of 0.01% CNT Nano fluids have been used in thermal optimization of micro channel heat sink (Halelfadl *et al.*, 2014), and the result dictated that the application of Nano fluid improved the convective heat transfer by 2% at 20°C, 12% at 30°C and 13% at 40°C. The application of metallic oxides in Nano fluid has also been an effective approach. Previously it has already been discussed the use of Al2O3 and CuO. SiO2 has also been used as nanoparticle to produce Nano fluid, but it hasn't shown that much influence than other Nano fluids. The use of TiO2/Water Nano fluid has brought some influential researches. A Theoretical modelling has been proposed using TiO2/water and ZnO/Water as Nano fluid in micro channel heat sink along with its optimization (Mukherjee *et al.*, 2018). The research concluded that ZnO/water provided a better performance that TiO2/water at the same pumping power. A numerical study (Martínez *et al.*, 2019) recorded a maximum increase of 19.66% in convective heat transfer coefficient at low Reynolds number when they compared TiO2 based Nano fluid to the pure water. Also, TiO2/Water Nano fluid was experimentally studied (Arshad and Ali, 2017) to investigate the pressure drop and heat transfer in a mini channel heat sink. Three different sets of models were used (Nitiapiruk *et al.*, 2013) in another study using TiO2 based Nano fluids to examine thermal conductivity and viscosity. The use of Graphene-based Nano fluid has been an important area of research. Balaji et al. (Balaji *et al.*, 2020) observed that the use of functionalized GnP based Nano fluid shows 11% higher maximum thermal conductivity, 13.3% viscosity, 71% higher convective heat transfer co-efficient and 60% enhancement in Nusselt number. Another study included the use of graphene-silver Nano fluid (Bahiraei and Heshmatian, 2018). It concludes that at the same pumping power Nano fluid possesses lower surface temperature and thermal resistance than pure water. Regarding the particle size of nanoparticle, there have been few researches. Qi et al. (Qi, Liang and Rao, 2016; Qi *et al.*, 2017) smaller radius of nanoparticles enhances the heat transfer across the heat sink. Particle ratio has also been an important criterion to enhance Nano fluid performance (Kumar and Sarkar, 2020).

2.5 Review on the application of Liquid metal:

Through more research and study, the concept of using Liquid metal as the base fluid in place of the commonly used base fluid has gotten more attention. Because of having meager Prandtl number, liquid metals have much higher heat conductivity than water and almost all the tradition fluids. Hyunsun Song et al. (Song *et al.*, 2020) have discussed the application of liquid metal across various fields of energy. Smither (Smither *et al.*, 1988) used liquid metal for heavy heat load and got remarkable feedback favoring using liquid metal. A wide range of research have certified the promising contribution of liquid metal in heat transfer applications. Initially, they have been used in nuclear reactors for cooling (Sawada *et al.*, 2000). Their introduction in mini channel heat sink have brought huge advancement in context of heat extraction and removal. Xiang et al (Xiang et al. 2018) compared cooling performance of water and liquid metal under similar micro channel heat sink conditions. Because of their consistent chemical property and better electrical conductivity, these fluids can be pumped without the help of any moving mechanism by magnetohydrodynamic (MHD) (Liu *et al.*, 2015). Later on, a comparison work has been carried out by Muhammad (Muhammad *et al.*, 2020) to show how various type of liquid metal behaves under multiple substrate materials and varying Reynolds number. Numerical investigation of laminar flow was conducted using liquid metal by Muhammad et al. (Muhammad, Selvakumar and Wu, 2020). Heat transfer performance was investigated by Liu (Liu, An and Wang, 2017) using GaInSn. Liquid metal with the ceramic substrate was used in mini channel heat sink [11]. These have further forged the background for the replacement of traditional fluids with liquid metal. Although liquid metal has a huge upside over other fluids, it experiences inevitable backlash when used in heat sink because of corrosion or chemical inadaptability (Barbier and Blanc, 1999; Deng and Liu, 2009). Substrate coating with molybdenum, nickel or tungsten is a vital way to overcome such difficulty (Tawk *et al.*, 2013). Ma et al. (Ma and Liu, 2007) have discussed the upsides of Nano liquid metal fluid over the traditional Nano fluids and further described how the large surface tension of liquid metal is more favorable for the higher volume fraction of nanoparticles.

Chapter 3: Methodology

This section presents the detailed methodology used in this study. The first part deals with the geometric modelling and the computational domain followed by the governing equations used in computational fluid dynamics to simulate single and multiphase fluid flow and heat transfer inside the microchannel heat sink. The later part discusses different parameters used in single and multiphase problems along with validation of the numerical model with experimental data obtained from (Lee and Mudawar, 2007).

3.1 Geometric model

The geometry used for this study is a microchannel heat sink containing 21 identical rectangular channels. The geometry parameters used in this study is taken from those presented by experimental works done by (Lee and Mudawar, 2007). Due to similar geometry of the channels, the computational domain is taken with three channels as presented in figure 2. The top surface of the heat sink was assumed to be having an adiabatic wall which generates a closed domain for fluid motion inside the mini channels. The study contains a numerical simulation of the fluid flow and heat transfer for a series of Reynolds number. It should be mentioned that the flow Reynolds number never exceeded 100. Due to which laminar flow regimes could be assumed for all the cases.

Table 1

Geometric parameter of the MCHS

Material	**MCHS height H (mm)**	**MCHS width W (mm)**	**MCHS length L mm**	**Channel width w_{ch} µm**	**Base thickness t_b µm**	**Channel wall thickness w_w µm**	**Channel height h_{ch} µm**
Copper	3.17	10	44.8	215	2349	261.2	821

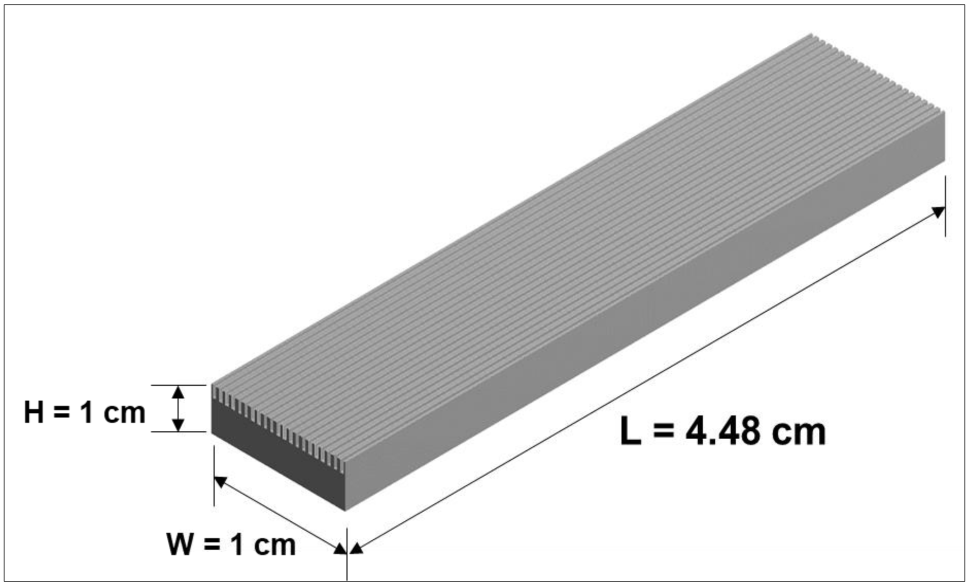

Figure 1. 3D Isometric view of the microchannel heat sink

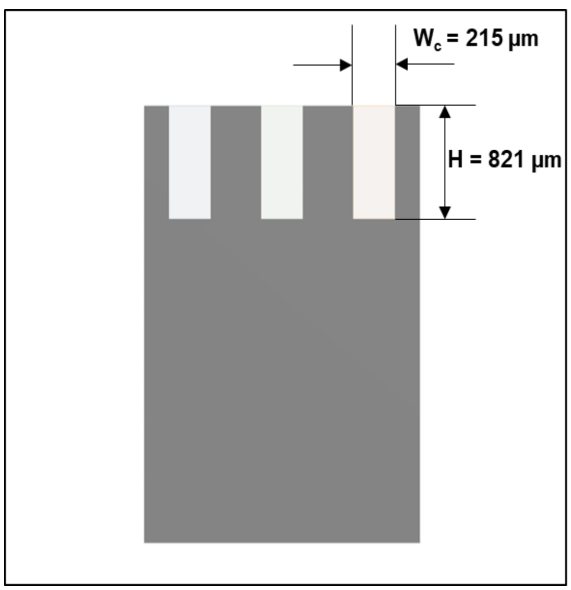

Figure 2. Front view of the computational domain

Due to identical geometry of 21 channels of the microchannel heat sink, all of the micro channels show identical heat transfer and fluid flow properties. Thus, three channels are taken into consideration for the computational domain.

3.2 Flow and Thermal model

From the given dimensions of the heat sink, input perimeters and numerical solution, flow and thermal comparative factors can be calculated. The friction factor for a single channel can be determined from:

$$f = \frac{\Delta P_{ch} D_h}{2L\rho_{nf}u^2} \tag{1}$$

Where,

$$\Delta P_{ch} = P_{in} - P_{out} \text{ and } D_h = \frac{4W_{ch}H_{ch}}{2(W_{ch} + H_{ch})} \tag{2}$$

Now, the overall pumping power required for the forced flow can be calculated from:

$$W = n\Delta P_{ch} A_{in} U_i \tag{3}$$

For calculating the heat transfer coefficient, the base fluid temperature difference is considered.

$$\overline{h} = \frac{q_f}{N\Delta T_{btd} A_{fin}} \tag{4}$$

In this equation, "q_f" represents total heat flux at the bottom of the heat sink.

Fin surface area, $A_{fin} = \left(W_{ch} + 2\eta_{fin}H_{ch}\right)L_{ch}$ and base fluid temperature difference, $\Delta T_{btd} = \overline{T_w} - 0.5(T_{in} + T_{out})$

$$\eta_{fin} = \frac{\tanh(mH_{ch})}{mH_{ch}} \tag{5}$$

$$m = \sqrt{\frac{2h}{k_s W_{fin}}} \tag{6}$$

So, the Nusselt number can be calculated:

$$\overline{Nu} = \frac{hD_h}{k} \tag{7}$$

3.3 Thermo-physical properties of the base fluid and nanoparticles

For single-phase analysis, thermo-physical properties of the mixture are required. For water-Al_2O_3, thermo-physical properties for different volume fractions are presented in table 2.

Table 2

Thermo-physical properties of water-Al_2O_3

	Water base					
	φ = 0%	1%	2%	3%	4%	5%
K_{nf} (W/m k)	0.603	0.620	0.638	0.656	0.675	0.693
P_{nf} (kg/m^3)	995.7	1021.7	1047.7	1073.8	1099.8	1125.9
μ_{nf} (kg/m s)	$7.977*10^{-4}$	$8.177*10^{-4}$	$8.376*10^{-4}$	$8.576*10^{-4}$	$8.775*10^{-4}$	$8.974*10^{-4}$
$C_{p,nf}$ (kJ/kg K)	4.183	4.149	4.115	4.081	4.046	4.018

For two-phase analysis, properties of the base fluid and particles are required separately. These properties are temperature-dependent functions and considered to be continuous over the entire domain. Base fluid properties are presented in table 3, and particles' properties in table 4.

Table 3

Thermal and physical properties of base fluid

Material	**Density (Kg/m^3)**	**Thermal conductivity (W/mK)**	**Specific heat (J/KgK)**	**Dynamic viscosity (×10^{-3}) (Pa.s)**
Water	995.7	.603	4183	$7.977*10^{-4}$
Ga	6090	31	429.9–0.275543T	1.8879
EGaInSn	6440	16.5	295	2.4
EGaIn	6280	26.6	404	1.99
GaSn	6300	30	365	2.192
GaIn	6363.2	39	365.4	2.210

Table 4

Thermal and physical properties of Nano-particles (Zhou *et al.*, 2018)

Particle	Density, ρ (Kg/m^3)	Thermal conductivity, k (W/mK)	Specific heat, C_p (J/KgK)
Al2O3	3600	36	0.765
Cu	8978	387.6	381
Diamond	3510	1000	497.26
CNT	1600	3000	796

3.4 Mathematical Formulation

The study consists of three different types of Numerical models to predict the heat transfer and flow phenomenon inside the micro channels accurately. The governing equations associated with these numerical models are described in this section.

3.4.1 Single-phase model

In a single-phase model, the Nano fluid is treated as a homogeneous fluid with continuous properties. The differential equations expressing conservation of mass, momentum, and energy are given (Moraveji *et al.*, 2011):

Continuity equation:

$$\nabla.(\rho_{nf}.V_m) = 0 \quad (8)$$

Momentum equation:

$$\nabla.(\rho_{nf}.V_m.V_M) = -\nabla P + \nabla.(\mu_{nf}.\nabla V_m) \quad (9)$$

Energy equation:

$$\nabla(\rho_{\mathrm{nf}}.C.V_m.T) = \nabla.(\mathrm{k}_{\mathrm{nf}}.\nabla\mathrm{T}) \tag{10}$$

The selection of suitable correlation plays a significant role in the precision of this model. There is no universal correlation yet, and in studies, they give contradictory results in different circumstances.(Mansour, Galanis and Nguyen, 2007) Nevertheless, all sources indicate that Nano fluid properties are dependent on the volume fraction and diameter of particles and dependent upon the temperature. The following formulas are used to calculate Nano fluid density, specific heat, viscosity, and thermal conductivity.

Density (Khanafer, Vafai and Lightstone, 2003):

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_s \tag{11}$$

Specific heat(Khanafer, Vafai and Lightstone, 2003):

$$\left(c_p\right)_{nf} = \frac{(1-\varphi)\rho_{bf}c_{p,bf} + \varphi\rho_s c_{p,s}}{\rho_{nf}} \tag{12}$$

Viscosity :(Keshavarz Moraveji and Hejazian, 2012)

$$\mu_{nf} = \mu_{bf}\left(\frac{1}{(1+\varphi)^{0.25}}\right) \tag{13}$$

Thermal conductivity :(Keshavarz Moraveji and Hejazian, 2012)

$$k_{nf} = \frac{k_s + (n-1)k_{bf} - (n-1)\varphi(k_{bf} - k_s)}{k_s + (m-1)k_{bf} + \varphi(k_{bf} - k_s)}k_{bf} \tag{14}$$

The particle volume fraction is denoted by φ, and the subscript s, bf, nf express particle, base fluid, and Nano fluid sequentially. The particles are assumed to be spherical with a shape factor n=3.

3.4.2 Two-phase model

The two-phase model recognizes the fluid domain as a liquid-solid mixture. There is two computational techniques for modeling such phenomena based upon volume fraction. The Eulerian-Lagrangian method is used for low volume fraction, whereas the Eulerian method is used to model the base fluid and the Lagrangian method to model the particle flow. For higher volume fractions, the Eulerian-Eulerian method is more suitable. In Nano fluids, the particle size is minimal. Even for a very low volume fraction, the number of particle is very high, making the computational domain's flow prediction pretty impossible by the Lagrangian-Eulerian method due to computing power limitation. This is why the Eulerian-Eulerian model is used. The most popular Eulerian-Eulerian methods are mixture, Eulerian and VOF.

3.4.2.1 *Mixture model*

The mixture model has become popular due to its computational simplicity. Its key feature is that only one set velocity constituent is solved for the momentum conservation equation of the mixture. The effect of the secondary phase on the primary phase via drag force and turbulence is considered. The prior assumptions of the mixture model are as follows:

- Pressure is deemed to be shared equally between phases.
- Secondary phase particle velocity and are extracted from algebraic formulation (El-Batsh, Doheim and Hassan, 2012).
- Nanoparticles are assumed to be spherical shaped
- phase slip considered for determination of secondary dispersed phase concentration.
- The mixture model is limited due to the following factors:
- Compressible property of the mixture isn't accounted
- Ideal gas law can be employed; hence pressure boundary conditions can't be implied
- The interaction between different dispersed phases are assumed minimum
- To avoid complexity turbulence generation due to the secondary phase and its effect on the primary-secondary phase interaction is neglected (El-Batsh, Doheim and Hassan, 2012).

The partial differential steady-state governing equations expressing the mixture model are presented as follows (Mokhtari Moghari *et al.*, 2011):

Continuity equation:

$$\nabla.(\rho_{nf}.V_m) = 0 \tag{15}$$

Momentum equation:

$$\nabla.(\rho_m.V_m.V_M) = -\nabla p + \nabla.(\mu_m.\nabla \mathrm{V_m}) + \nabla.(\sum_{k-1}^{n} \varphi_k \rho_k V_{dr,k}) - \rho_{m,i}\, \beta_m g(T - T_i) \quad (16)$$

Energy equation:

$$\nabla \sum_{k-1}^{n} \left(\rho_k.C_{pk}.\varphi_k.V_k.T\right) = \nabla.(\mathrm{k_m}.\nabla \mathrm{T}) \quad (17)$$

Volume fraction equation:

$$\nabla.\left(\varphi_\mathrm{p}\rho_p V_m\right) = -\nabla.(\varphi_\mathrm{p}\rho_p V_{dr,p}) \quad (18)$$

where the mixture velocity, density and viscosity are respectively defined as:

$$V_m = \frac{\sum_{k=1}^{n} \varphi_k \rho_k V_k}{\rho_m} \quad (19)$$

$$\rho_m = \sum_{k=1}^{n} \varphi_k \rho_k \quad (20)$$

$$\mu_m = \sum_{k=1}^{n} \varphi_k \mu_k \quad (21)$$

The secondary phase is denoted by 'k'. The corresponding relative velocity relates to the drift velocity of the secondary phase.

$$V_{dr,k} = V_{pf} - \sum_{k=1}^{n} \frac{\varphi_k \rho_k}{\rho_m} V_{fk} \quad (22)$$

Similarly, the nanoparticle's relative velocity (represented by 'p') relative to the base fluid (represented by 'f') is defined as the slip velocity.

$$V_{pf} = V_p - V_f \tag{23}$$

$$V_{pf} = \frac{\rho_p d_p^2}{18\mu_f f_{drag}} \frac{(\rho_p - \rho_m)}{\rho_p} a \tag{24}$$

$$f_{drag} = f(x) = \begin{cases} 1 + 0.15Re_p^{0.687}, & Re_p \leq 1000 \\ 0.0183Re_p, & Re_p > 1000 \end{cases} \tag{25}$$

Where Reynolds number 'Rep' and acceleration 'a' can be found in the following equations:

$$Re_p = \frac{V_m d_p}{\vartheta} \tag{26}$$

$$a = g - (V_m.\nabla)V_m \tag{27}$$

3.4.2.2 *Eulerian Model*

In this model, the pressure is presumed to be equal for all the phases. The governing equations are solved separately for primary and secondary phases. By integrating the corresponding domain's volume, each phase's volume fraction can be calculated.

$$\nabla.\left(\rho_l \varphi_l \overrightarrow{V_l}\right) = 0 \tag{28}$$

$$\nabla.\left(\rho_p \varphi_p \overrightarrow{V_p}\right) = 0 \tag{29}$$

The summation of the volume fraction of the phases is considered to be one(Akbari, Galanis and Behzadmehr, 2011).

$$\varphi_l + \varphi_p = 0 \tag{30}$$

The Eulerian model corresponding equations can be expressed as follows (Kalteh *et al.*, 2012):

$$\nabla.\left(\rho_l \varphi_l \overrightarrow{V_l}\overrightarrow{V_l}\right) = -\varphi_l \nabla p + \nabla.\left[\varphi_l \mu_l (\nabla\overrightarrow{V_l} + \nabla\overrightarrow{V_l}T)\right] + F_d + F_m \tag{31}$$

$$\nabla.\left(\rho_p \varphi_p \overrightarrow{V_p}\overrightarrow{V_p}\right) = -\varphi_p \nabla p + \nabla.\left[\varphi_p \mu_p (\nabla\overrightarrow{V_p} + \nabla\overrightarrow{V_p}T)\right] - F_d + F_{vm} + F_{col} \tag{32}$$

In our study, lift force can be ignored due to the small size of particles. Drag force can be determined by:

$$F_d = -\beta(\overrightarrow{V_l} - \overrightarrow{V_p}) \tag{33}$$

In this equation, 'β' represents the friction coefficient. Its value depends upon the volume friction. For a very dilute two-phase flow with particle diameter dp, the friction coefficient is:

$$\beta = \frac{3}{4} C_d \frac{\varphi_l(1-\varphi_l)}{d_p} \rho_l \left|\overrightarrow{V_l} - \overrightarrow{V_p}\right| \varphi_l^{-2.65} \tag{34}$$

This equation is valid when $\varphi_l > 0.8$. Here, C_d is the drag coefficient and dependent upon the particle's Reynolds number.

$$C_d = \begin{cases} \frac{24}{Re_p}(1 + 0.16 Re_p^{0.687}), & Re_p < 1000 \\ 0.44, & Re_p \geq 1000 \end{cases} \tag{35}$$

Where,

$$Re_p = \frac{\varphi_l \rho_l \left|\overrightarrow{V_l} - \overrightarrow{V_p}\right| d_p}{\mu_l} \tag{36}$$

Assuming the mixture composed of incompressible constituents and the viscous dissipation and radiation is negligible, the energy equation can be expressed as:

$$\nabla.\left(\rho_l \varphi_l C_{pl} T_l \overrightarrow{V_l}\right) = \nabla.\left(\varphi_l k_{eff,l} \nabla T_l\right) - h_v(T_l - T_p) \tag{37}$$

$$\nabla.\left(\rho_p \varphi_p C_{pp} T_p \overrightarrow{V_p}\right) = \nabla.\left(\varphi_p k_{eff,p} \nabla T_p\right) + h_v (T_l - T_p) \tag{38}$$

For mono-dispersed spherical particles, h_v can be calculated from:

$$h_v = \frac{6(1-\varphi_l)}{d_p} h_p \tag{39}$$

Where, 'h_p' represents particle heat transfer coefficient, which can be calculated from the following empirical question:

$$Nu_p = \frac{h_p d_p}{k_l} = 2 + 1.1 Re_p^{0.6} \mathrm{Pr}^{\frac{1}{3}} \tag{40}$$

The effective thermal conductivity of the related phases are evaluated as:

$$k_{eff,l} = \frac{k_{b,l}}{\varphi_l} \tag{41}$$

$$k_{eff,p} = \frac{k_{b,p}}{\varphi_p} \tag{42}$$

Where,

$$k_{b,l} = \left(1 - \sqrt{(1-\varphi_l}\right) k_l \tag{43}$$

$$k_{b,} = \sqrt{(1-\varphi_l)}(\omega A + [1-\omega]\Gamma) k_l \tag{44}$$

and

$$\Gamma = \frac{2}{(1-\frac{B}{A})} \{ \frac{B(A-1)}{A\left(1-\frac{B}{A}\right)^2} \ln\left(\frac{A}{B}\right) - \frac{(B-1)}{\left(1-\frac{B}{A}\right)} - \frac{B+1}{2} \} \tag{45}$$

Here,

$$B = 1.25 \left(\frac{[1-\varphi_l]}{\varphi_l}\right)^{\frac{10}{9}} \tag{46}$$

For, spherical nanoparticle,

$$A = \frac{k_p}{k_l} \; and \; \omega = 7.26 * 10^{-6} \qquad (47)$$

3.4.2.3 *VOF model*

The VOF model includes the study of the entire domain. The volume fraction of each phase is calculated by solving the continuity equation of the secondary phase. Overall volume fraction of the domain is assumed to be one. The corresponding phase's velocity element is evaluated by solving one set of momentum equation. A weighted average of different phases is taken to calculate the physical properties, based upon their volume fraction throughout each control volume. In this model, velocity elements and temperature are considered to be shared between phases. Mass conservation is expressed as (Akbari, Galanis and Behzadmehr, 2012):

$$\nabla . \left(\rho_p \varphi_p \overrightarrow{V_p} \right) = 0 \qquad (48)$$

Where, $\sum_{k=1}^{n} \varphi_k = 1$, and properties are calculated by, $N = \sum_{q=1}^{n} \varphi_q N_q = 1$.

The partial differential equations for conservation of momentum and energy are similar to equation.

3.5 Numerical Model

This study contains implementation of different numerical models to accurately predict flow and thermal performance of Nano liquid metal fluid inside a micro channel heat sink. This section presents the boundary conditions, solution parameters and the validation of the numerical method with experimental data available in literature.

3.5.1 Boundary conditions

The boundary conditions used in the numerical analysis are explained below. All the boundary conditions used by (Lee and Mudawar, 2007) are followed in this study for the validation and further analysis.

For the solid domain,

Constant heat flux per unit area ($q_b = 100\ W/cm^2$) was applied at the bottom wall ($y = 0$). The symmetry boundary condition was applied at the left and right walls ($x = 0, x = W_w + W_c$). The adiabatic wall boundary condition was applied at the top wall, the front and back wall of the sink ($y = H + t_b,\ z = 0,\ z = L$). No-slip boundary conditions at the fluid-solid interface.

For the fluid domain,

Uniform velocity (U_{in}) with constant temperature (T_{in}) was applied at the inlet ($z = 0$). Pressure outlet was applied at the outlet ($z = 0$).

3.5.2 Solution parameters

ANSYS FLUENT 19.0 was used for the numerical analysis. Pressure based 3D segregated solver was used which is based on the finite volume method. The computational domain was discretized with structured 3D hexahedral cells generated by the software *ICEMCFD 19.0*. The convective heat flux and the momentum equation was obtained by the second-order upwind scheme. The diffusive flux was computed with the second central differencing scheme. The classical SIMPLE algorithm was used for the pressure-velocity coupling. The under-relaxation factors used were for pressure $= 0.3$, momentum $= 0.7$ and energy $= 1$. Qualitative convergence had been judged by residual falling below 10^{-6} for continuity and the velocity components and below 10^{-10} for energy. The Quantitative convergence was judged by average heat source temperature and pressure at inlet remaining unchanged with subsequent iterations.

3.5.3 Validation and Mesh Independence

The numerical method used in this study was validated against experimental data presented in (Lee and Mudawar, 2007). Firstly, the results obtained from single phase method and mixture model (two phase method) are compared with the experimental data as presented in figure. A good consistency can be found between numerical data and experimental data.

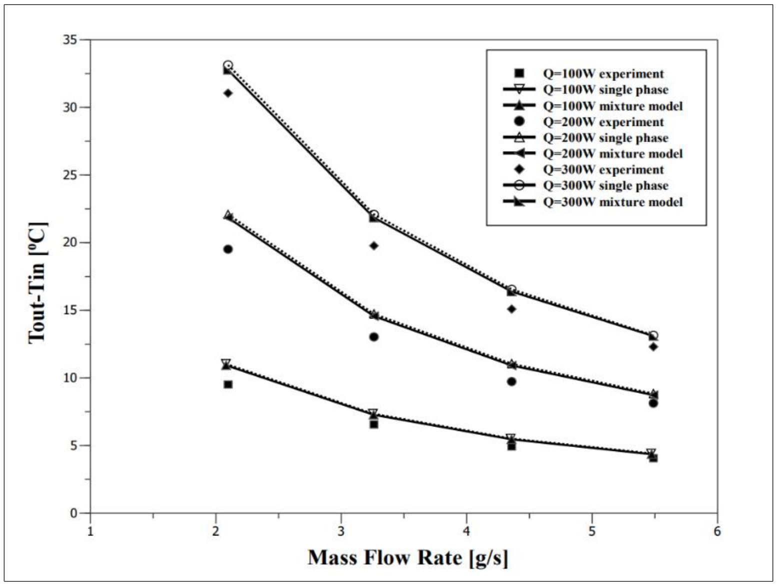

Figure 3. Comparison of numerical data with experimental data

Three different sets of grids were generated for the numerical model. All of the generated grids were used for comparing the solution accuracy with the experimental data. Two factors were considered for the grid test. The first parameter was the accuracy of the grid to reach optimum solution closer to the experimental data. The second thing for consideration was the time required for the solver to reach the convergence. Different grids generated are shown in figure 2.

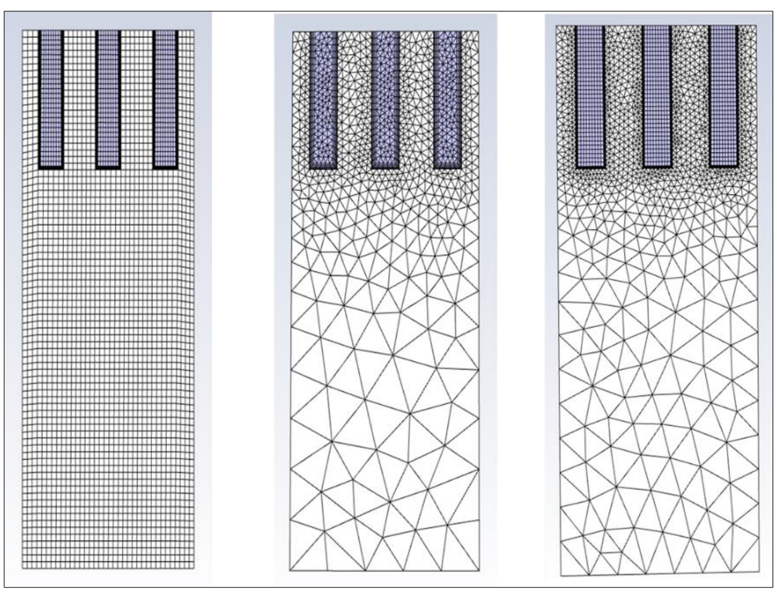

Figure 4. Grids generated for the study

The first set of grid contained structured hexahedral cells for both solid and fluid domains. The next grid type contained unstructured tetrahedral cells for solid and fluid domains and the other type of grid contained structured hexahedral cells for fluid domain while the solid domain contained tetrahedral unstructured cells.

The comparison of numerical results with experimental data presented in (Lee and Mudawar, 2007) with different grids generated are presented in table 5. The solutions are in very good agreement with the experimental data with all of the generated grids. Though all of the generated grids show very good agreement, the structured mesh generated with hexahedral elements showed lesser time to reach the convergence. Thus, the grid generated with structured hexahedral elements are selected for the numerical analysis.

Table 5

Solution comparison with different grids

Mesh type	**Number of elements**	**Outlet temp (Numerical)**	**Experimental outlet temperature**	**Error**
Structured	1.4 million	314.0442 K	312.489 K	0.4983%
	3.7 million	314.0435 K	312.489 K	0.4974%
	5.7 million	314.0431 K	312.489 K	0.4971%
Unstructured	2.4 million	314.0445 K	312.489 K	0.4978%
	4.7 million	314.0441 K	312.489 K	0.4976%
	6.7 million	314.0421 K	312.489 K	0.4974%
Unstructured + Structured	3.7 million	314.0434 K	312.489 K	0.4974%
	5.4 million	314.0432 K	312.489 K	0.4952%
	6.5 million	314.0429 K	312.489 K	0.4922%

3.5.4 Convergence criterion

Two different type of inspection were performed to check the convergence of the numerical analysis. The first one was quantitative convergence which was checked by monitoring all of the residuals. The other method was to check any variable at any certain boundary of the numerical model which is termed as qualitative convergence.

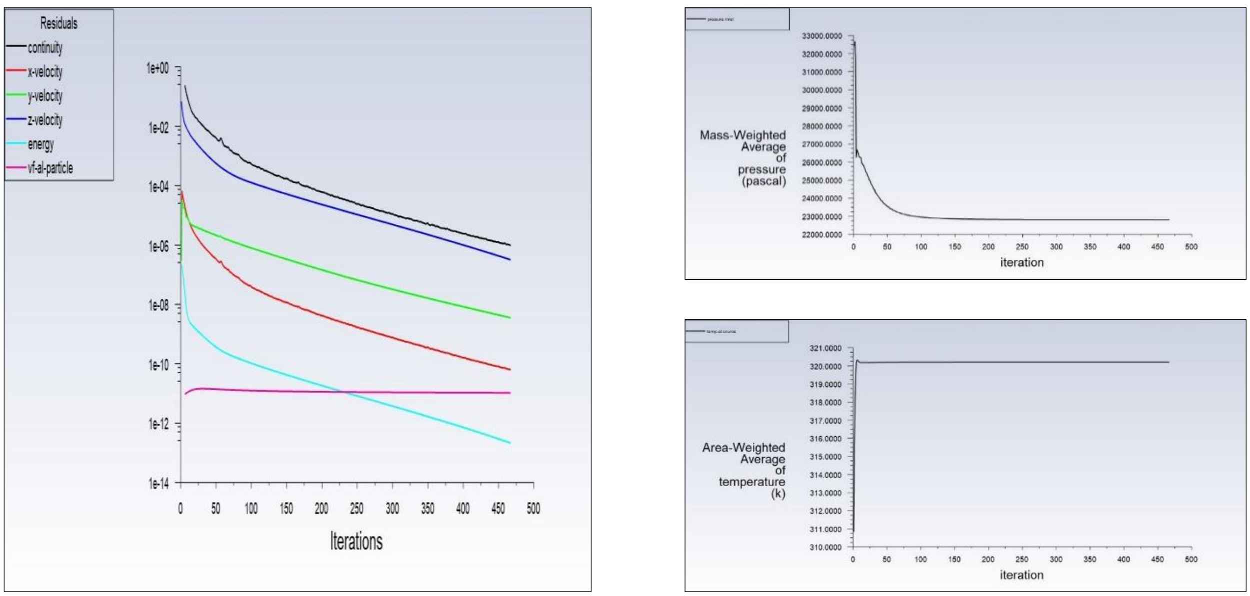

Figure 5. Convergence criterion of the solver

Chapter 4: Result and Discussion

This section presents the detailed results obtained from the study. The results are presented sequentially in a number of subsections. At first the thermal and hydraulic performance of different liquid metal-based Nano fluids are compared with that of water using the same Nano particles in preparing the Nano fluids for 2% particle concentration. The thermal performance is compared using the average heat transfer obtained by different coolants. The hydraulic performance is compared by the pressure drop resulting in transporting the Nanofluids through the microchannels. The comparison is done using experimental data available in the literature with the numerical data obtained in this study. The results and conclusions presented in this study are also compared with the literature. A good consistency is noticed between the results in this study with that of the literature.

In order to provide a diverse perspective, base fluid performance comparison is proceeded for the same inlet velocity for the same particle with 2% concentration. This analysis is based on numerical data obtained from two-phase mixture model simulations. This study consolidates the improvement of thermal performance, using liquid metal base fluids in place of water.

The cooling effectiveness is also analyzed by comparing channel surface temperature, and fluid mean temperature along the sink length. Finally, the heat sink's overall performance for different base fluid is also examined by introducing 'PEC', which accounts for both the thermal enhancement and energy cost of pumping.

The effect of different nanoparticles is also studied for different base liquid metal fluids for the same particle concentration. This study provides the Nano fluid combination having the highest heat transfer coefficient.

Finally, the effect of particle concentration on thermal and hydraulic performance has been studied along with inspection of visual cooling effectiveness to provide assistance and guidance for further practical and detailed research approaches.

4.1 Comparison of Nano-liquid-metal-fluid with water-based Nano fluid

The results obtained from numerical simulations are compared with the experimental data obtained from (Lee and Mudawar, 2007). Due to similarity in geometry and other boundary conditions, the data obtained from experimental work presented in (Lee and Mudawar, 2007) using Al_2O_3-water (2% particle concentration) Nanofluid as the coolant is used for the performance comparison. The average heat transfer coefficient obtained through numerical simulations with similar boundary conditions and particle concentration are presented in figure 6. The study is carried out with a range of Reynolds numbers keeping consistency with the experimental data.

4.1.1 Thermal and hydraulic performance comparison with experimental data

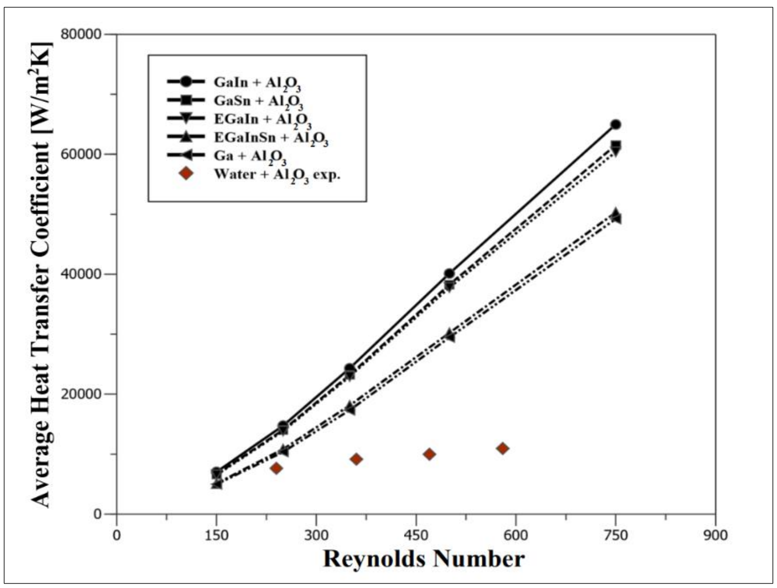

Figure 6. Comparison of thermal performance between liquid metal based Nano fluids with water based Nano fluid

The results presented in figure 6 shows that average heat transfer coefficient of liquid metal based Nano-fluids is much superior compared to that of water-based Nano fluid. At lower Reynolds number, all of the coolants show quite similar thermal performance. But while increasing the flow Reynolds number, an increase in the average heat transfer coefficient was noticed for all the liquid metal based Nano fluids. But, the experimental data obtained from (Lee and Mudawar, 2007) suggests that, at higher Reynolds number the average heat transfer coefficient does not show much improvements for water based Nano fluids.

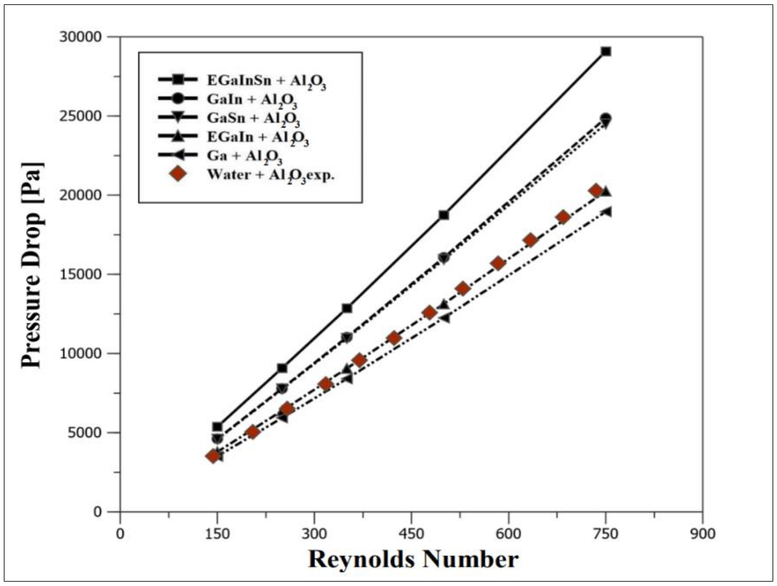

Figure 7. Comparison of hydraulic performance between liquid metal based Nano fluids with water based Nano fluid

The pressure drop resulting in transporting the liquid metal Nano fluids through micro channels is compared with similar boundary conditions (Lee and Mudawar, 2007). The experimental data obtained in the literature is plotted with the data achieved from numerical simulations. It is noticed that, liquid metal Nano fluids results in more pressure drop with respect to the water-based Nano fluid due to high density and viscosity of liquid metals compared to water. Though water based Nano fluid shows higher pressure drop than Ga and EGaIn based Nano fluids, conclusions cannot be reached from this comparison since with the same Reynolds number the inlet velocity of water-based Nano fluid is far more than liquid metal Nano fluids due to much lower density and viscosity of water. Thus, further analysis is made with the same inlet velocity (figure 8) to obtain the overall picture of the hydraulic performance.

4.1.2 Thermal and hydraulic performance comparison with the same inlet velocity

For further analysis, a similar comparison study was also conducted, keeping the inlet velocity the same for all the coolants at the same particle concentration. The average heat transfer coefficient obtained at different inlet velocities with all the coolants is presented in figure 8.

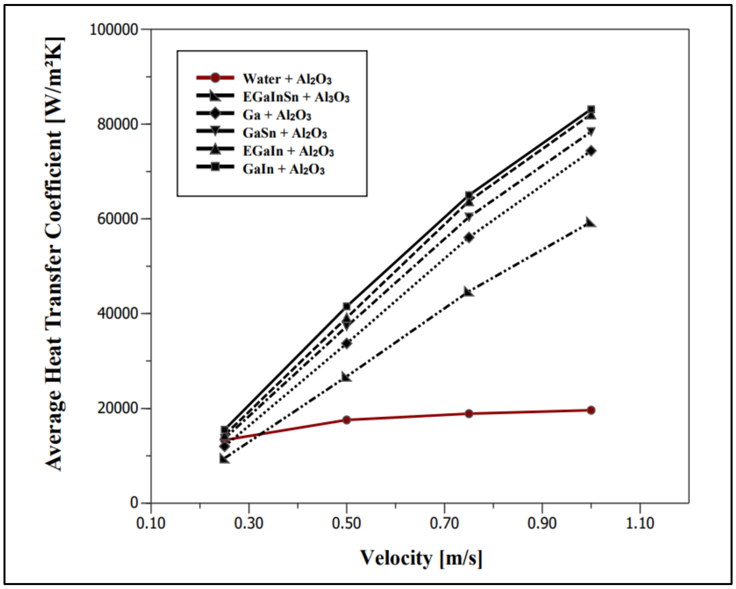

Figure 8. Comparison of thermal performance with same inlet velocity

The results presented in figure 8 show quite identical thermal performance as figure 6. The average heat transfer coefficient of water-based Nano fluid does not show much improvements at higher velocity. On the other hand, liquid metal-based Nano fluids show much improvements at higher velocity. These attributes can be explained by analyzing the thermal properties of different coolants in this study. In case of microchannel heat sink, the dominating property in characterizing the heat transfer performance is influenced by forced convective heat transfer. The convective heat transfer effect mainly depends on the flow velocity, specific heat transfer coefficient and thermal conductivity of the fluid. By analyzing the thermal properties of different Nano fluids as mentioned in Table 3, it is evident that, liquid metal-based Nano fluids will outperform water-based Nano fluid.

Though liquid metal-based Nano fluids show superior heat transfer than water-based Nano fluid, it also comes with a higher pressure drop penalty, resulting in more pumping power. The pressure drop inside the micro channels at different flow Reynolds number is presented in figure 7.

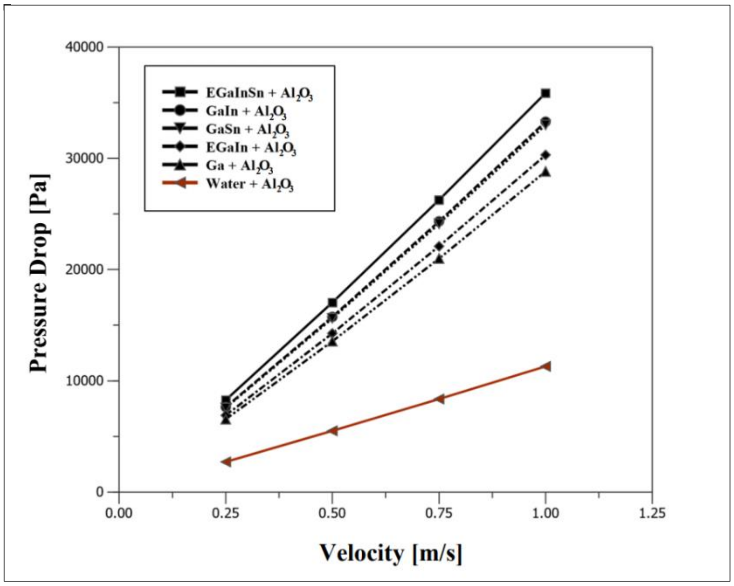

Figure 9. Comparison of hydraulic performance with same inlet velocity

The total pumping power required to push the coolant inside the micro channels are presented at different inlet velocities in figure 9. Liquid metal-based Nano fluids requires much more pumping power at the same inlet velocities than water-based Nano fluid. This phenomenon occurs due to much higher density and viscosity of the liquid metals than water. Among them, EGaInSn requires the most pumping power, and Ga requires the lowest pumping power.

4.1.3 Substrate and fluid temperature comparison along the channel length

The substrate wall temperature of the microchannel heat sink along the channel length using different Nano fluids is presented in this section to analyze the thermal performance of different coolants. The analysis has been carried out for Re=500 and α_p=0.02. The results show consistency with increasing temperature along with the length, as suggested in (Zhou *et al.*, 2018). Among liquid metal-based Nano fluids, as GaIn based Nano fluids have higher thermal conductivity, they tend to reduce the surface temperature lower for the same Reynolds number. But as water has a substantial higher velocity for the same Reynolds number than liquid metals because of considerably lower density, water-based Nano fluids tends to reduce the surface temperature much lower.

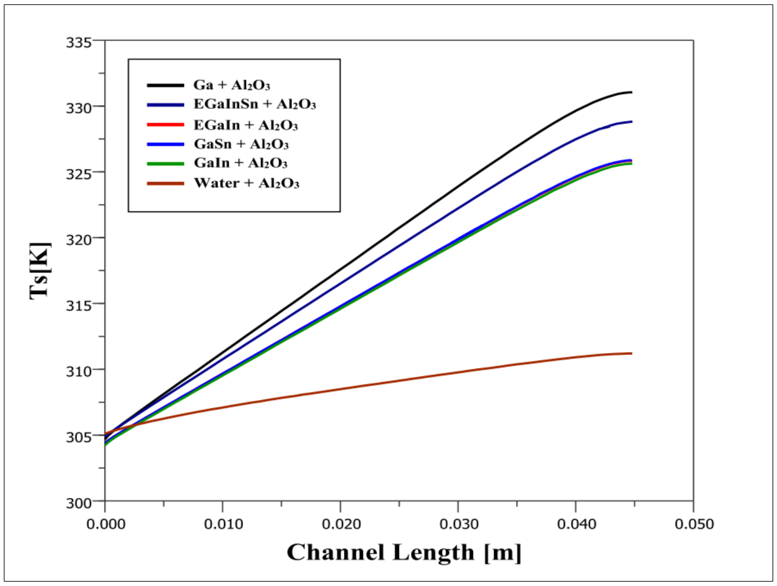

Figure 10. Substrate wall temperature along channel length

The next figure shows the mean fluid temperature along the channel length using different Nano fluids. The pattern of this figure shows consistency with the figure of surface temperature as they are both proportional to each other.

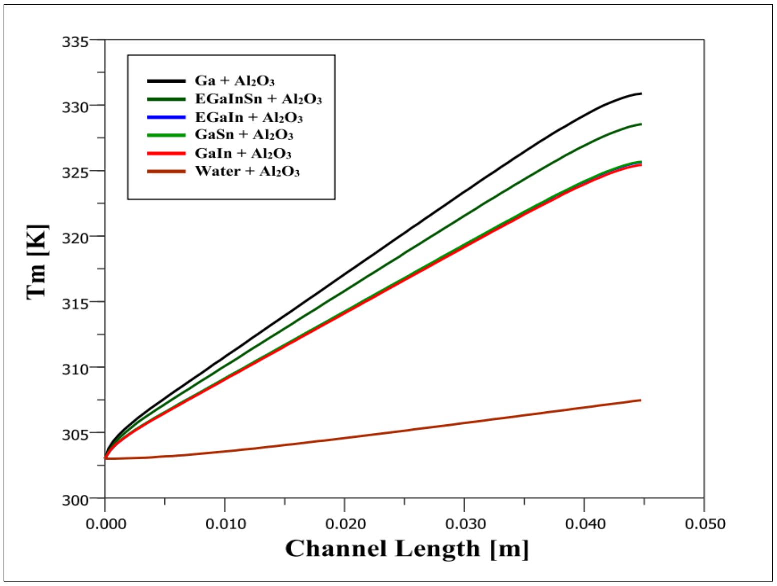

Figure 11. Fluid mean temperature along the channel length

As noticed in figure 10 and 11, although for the same Reynolds number water-based nanoparticle has lower heat transfer coefficient, but they have higher cooling effectiveness. Because heat transfer coefficient depends upon the bulk mean temperature difference. As water has lower conductivity, the difference is higher; thus, the heat transfer coefficient is lower. But as at the same Reynolds number, water can be passed at a higher velocity, reducing the sink surface temperature lower than the liquid metal-based Nano fluids.

4.1.4 Performance Evaluation Criterion

From the above discussion, it is evident that Nano-liquid-metal-fluids shows superior heat transfer coefficient than water based Nano fluid. But this cooling agents also require higher pumping powers to function properly. So, a new parameter termed as 'Performance Evaluation Criterion' (PEC) is introduced (Bianco et. al and Roy et. al). This parameter relates the heat transfer rate with the pumping power requirements to evaluate the overall performance of cooling agents.

$$PEC = \frac{m.C_p.(T_{out} - T_{in})}{V.\Delta P}$$

Where, m is the mass flow rate, C_p is the specific heat transfer coefficient, T_{out} and T_{in} are the outlet and inlet temperatures respectively, V is the volumetric flow rate and ΔP is the pressure drop inside the micro channels.

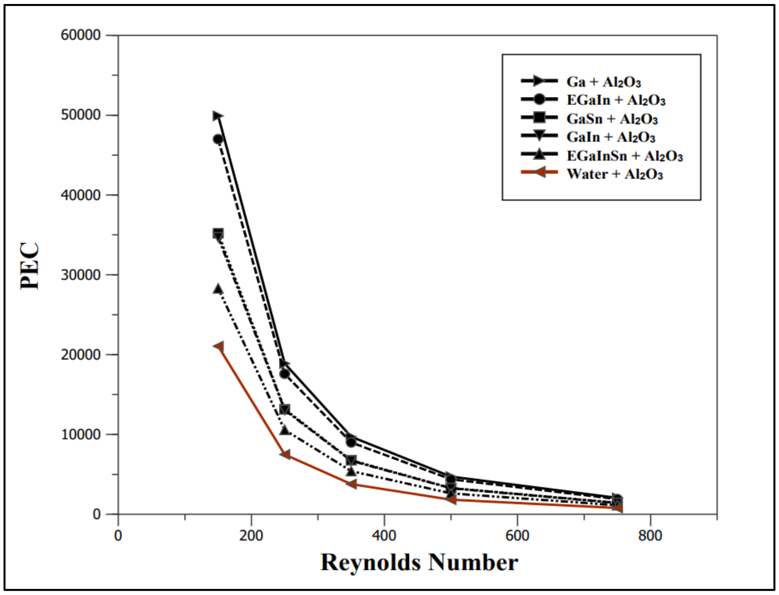

Figure 12. Comparison of Performance Evaluation Criterion between Nano-liquid-metal-fluids and water based Nano fluid

From figure 12, It has been found that for the same concentration of 2%, the increase of Reynolds number results in the reduction of PEC. This changing tendency shows that the energetic cost of pumping power is much higher than the corresponding heat transfer enhancement benefit (Zhou *et al.*, 2018). At a lower Reynolds number, the thermal performance of Nano fluids is dominating. For this reason, the variation in different base fluid's "PEC" is noticeable. But with increasing Reynolds number, the thermal effect lessens in respect of pumping performance and the variation in PEC reduces. So that the overall performance of different base fluids becomes similar at a higher Reynolds number.

Liquid metal based Nano fluids have considerably higher PEC than water-based Nano fluid irrespective of Reynolds number. This indicates the higher thermal benefit of using liquid metal as base fluid than water, considering the cost of pumping power.

4.2 Comparison of the influence of different nanoparticles

4.2.1 Thermal performance comparison

This section presents a comparative thermal performance comparison between different widely used Nanoparticles available in the literature. Four different types of Nanoparticles of the same concentration of 2% are used with the liquid metal solvents, and the average heat transfer coefficient is calculated for all the combinations. The comparison is presented in figure 13.

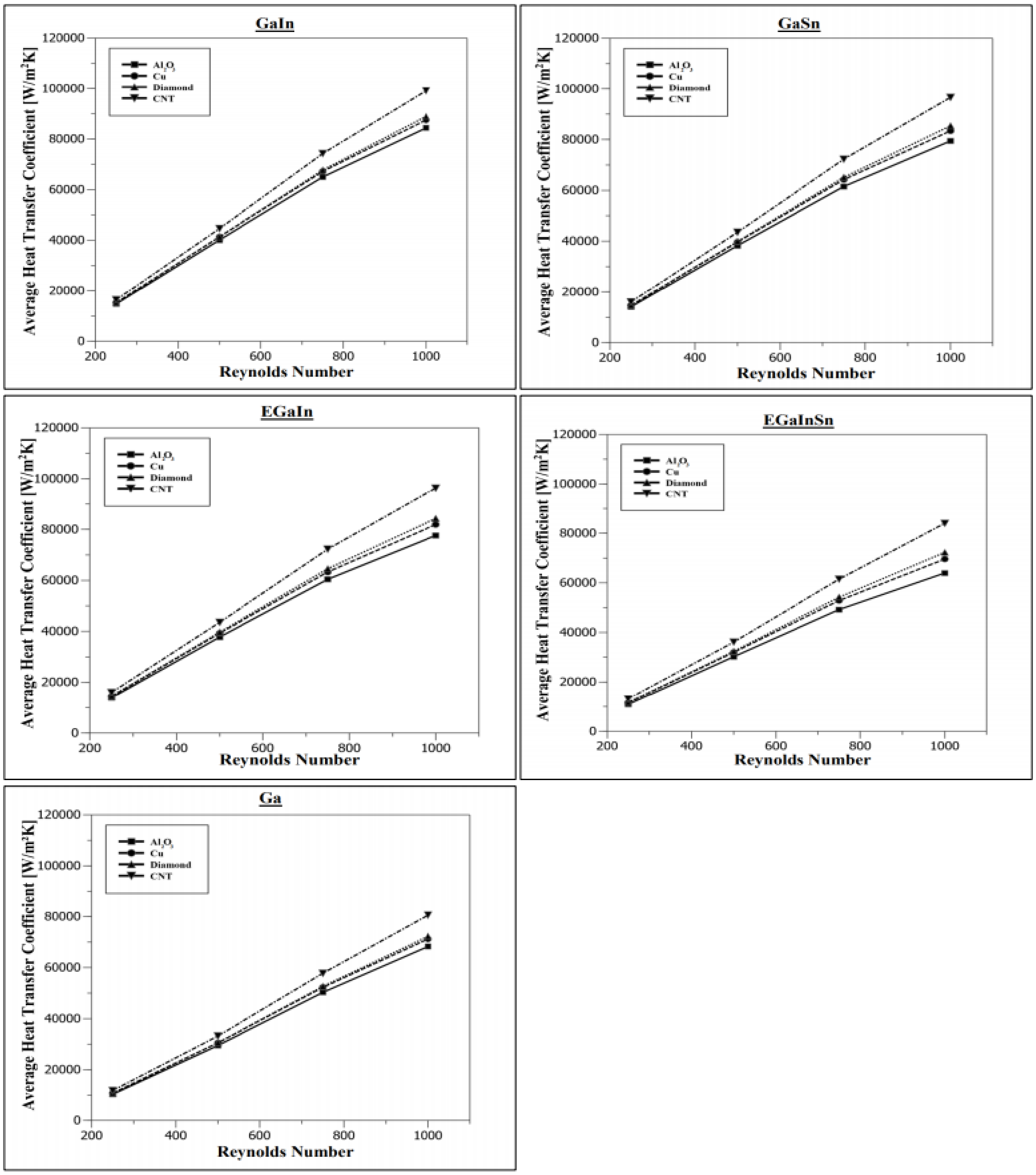

Figure 13. Comparison of thermal performance between different Nanoparticles

At lower Reynolds number, all the particles display the same thermal characteristics. But with the Reynolds number increasing, the effect of different particles is evident. It can be noticed that irrespective of the base fluid, CNT particle-based Nano fluids provides a higher thermal performance because of their higher thermal conductivity. Higher the Reynolds number, higher the increased percentage of heat transfer coefficient compared to other particles.

So it's determined that the GaIn-CNT mixture exhibits the highest thermal performance. For GaIn as base fluid and Re=750, CNT particle has an enhancement of 12.48%, 9.48%, 8.79% over Al_2O_3, Cu, and Diamond particle. And for the same Reynolds number, the GaIn-CNT mixture has a heat transfer coefficient increment of 2.68%, 17.19%, 22.16%, 2.62% over CNT particle-based EGaIn EGaInSn, Ga, GaSn liquid metal, respectively.

4.2.2 Hydraulic Performance comparison

The incorporation of different particles of the same diameter at the same concentration of 2% results in an unnoticeable change in viscosity and density. As a consequence, the change in pressure drop and pumping power is also trivial and insignificant. The effect of particle on pressure drop, pumping power and friction factor for GaIn based Nano fluid is presented in table 6.

Table 6

Hydraulic performance for different nanoparticle

Reynolds Number	Particle				
		Al_2O_3	Cu	CNT	Cu
Re=500	Pressure Drop (kPa)	16.067	16.084	16.059	16.065
	Friction factor	0.03737911	0.036792227	0.037599858	0.037386522
	Pumping power (10^{-3} W)	30.329694	30.36254	30.315348	30.327051
Re=750	Pressure Drop (kPa)	24.867	24.903	24.851	24.864
	Friction factor	0.025712882	0.025318185	0.02586022	0.025716912
	Pumping power (10^{-3} W)	70.414745	70.516114	70.369157	70.405684

Re=1000	Pressure Drop (kPa)	33.952	34.041	33.920	33.961
	Friction factor	0.019747277	0.019467097	0.019854626	0.019757975
	Pumping power (10^{-3} W)	128.184723	128.520734	128.064288	128.217569

4.3 Comparison of Nanoparticles volume fraction influence on heat sink performance

GaIn-CNT has been chosen over other combination due to its outstanding heat transfer characteristics. Different particle concentration ranging from 1-5% has been studied. The range has been selected based upon the fact that for higher particle concentration, the hydraulic and thermal performance effect is very negligible in microchannel heat sink. Also, it's hard to predict the nature of the flow, due to agglomeration of particle and clogging of the small channels in higher concentration. For this reason, a practical approach is required for detailed analysis consisting of consideration of all the factors. Our study tried to assume the outcome of increasing or decreasing particle concentration on thermal and hydraulic performance. Existing literature also proves the integrity and favorable outcome of our study.

4.3.1 Thermal performance comparison

Fig 14 presents the effect of nanoparticle volume fraction on the convective heat transfer coefficient. The different volume fraction of Nano liquid metal fluid GaIn-CNT has been studied for Reynolds number ranging from 250-750 and q=100 W/m^2. It has been found from the results that with concentration increasing, the thermal conductivity of the mixture also increases hence heat transfer coefficient increases. Existing literature(Lee and Mudawar, 2007) agrees with the increment in conductivity and heat transfer coefficient with particle concentration increment.

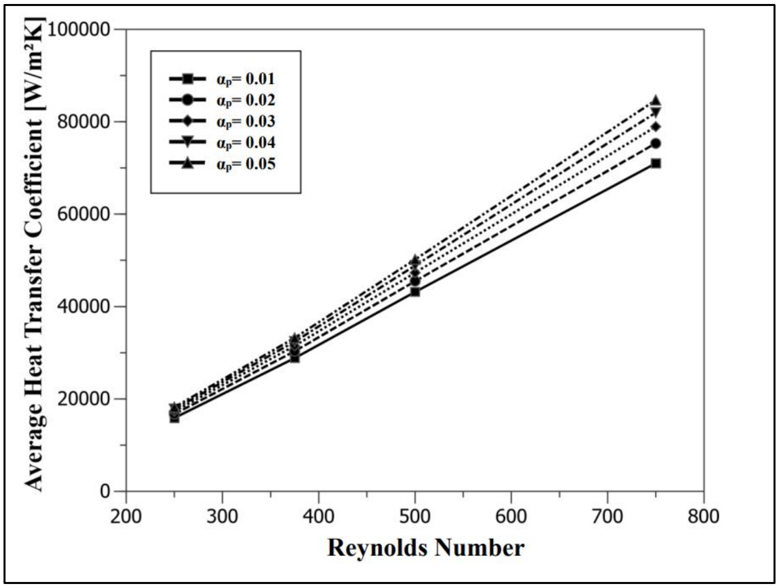

Figure 14. Comparison of thermal performance with different volume fraction of Nano fluids

The effect of the concentration increase is not linear. For re=500, increasing concentration from 1% to 2% increases heat transfer coefficient by 5.35% whereas for the same increment from 4- 5% heat transfer coefficient increases by 2.73%. So, the thermal performance enhancement gradually decreases with concentration increasing and becomes negligible for a higher concentration. This nonlinear effect of particle concentration is also evident from the existing literature.

Reynolds number increment results in the increment of the heat transfer coefficient, but this effect is not linear with particle concentration variation. For Re=250. Increment of concentration from 1% to 2% results in a 5.23% increase of heat transfer coefficient where for re=750, the increment of concentration for the same range results in 6.13% heat transfer coefficient increase. For increasing Reynolds number, concentration difference has a higher effect on thermal performance. This finding suggests similarity with the literature (Zhou *et al.*, 2018) about the effect of Reynolds number on thermal performance for different particle concentration.

4.3.2 Hydraulic performance comparison

Fig 15 presents the effect of particle concentration on pressure drop and corresponding pumping power. With particle concentration increasing, the viscosity of the mixture also increases. This is evident from Table 3 which is presented in (Lee and Mudawar, 2007) for water-based Nano fluids.

(Zhou *et al.*, 2018) also depicts the increase of viscosity with particle concentration for Nano liquid metal. With mixture viscosity increase, the increment of concentration results in higher pressure drop and pumping power for the same Reynolds number. But the effect of increment is not linear. For re =500, increasing concentration from 1-2% results in 3.8% viscosity increase and corresponding 3.09% increase in pressure drop where the same increment of concentration from 4-5% results in 2.27% increase in viscosity and corresponding 2.25% increase in pressure drop. So with particle concentration increasing, its effect on hydraulic performance decreases.

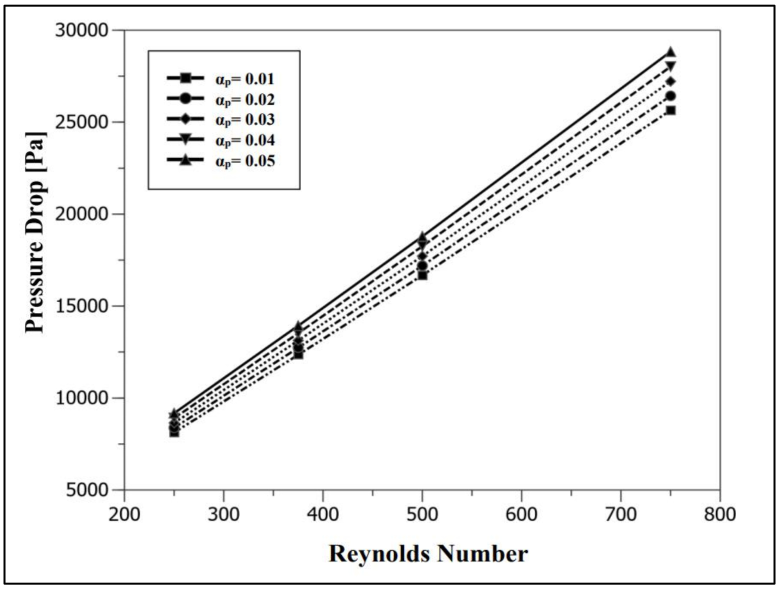

Figure 15. Comparison of hydraulic performance with different volume fraction of Nano fluids

For Reynolds number increasing pressure drop also increases linearly as suggested in the literature (Zhou *et al.*, 2018). For re=250, the increment of concentration from 1-2% results in a 3.16% increase in pressure drop where for re=750, the same increment in the same range pressure drop increases by about 3.01 %. So the effect of concentration increment with the variation of Reynolds number is negligible.

4.3.3 Substrate and fluid temperature comparison along the channel length

Figure 16 presents the effect of particle concentration on channel surface temperature. With particle concentration increasing, the thermal conductivity increases, but specific heat decreases. As the conductivity increases, the mixture will have more thermal capability. But with decreasing specific heat capacity, the absorbance capacity will be reduced. Figure 16 shows the net effect of increasing thermal conductivity and decreasing specific heat on the wall temperature, which is perhaps the most realistic measure of a given cooling scheme's effectiveness. Near the inlet, the decrease in surface temperature is noticeable. But at all other locations, the effect is virtually unnoticeable. At the inlet increasing concentration from 4-5% results in a 0.033% temperature decrease, where at the outlet the same reduction of amplitude for the same range results in .023% decrease. This finding and graph characteristic agrees with (Lee and Mudawar, 2007) and (Zhou *et al.*, 2018).

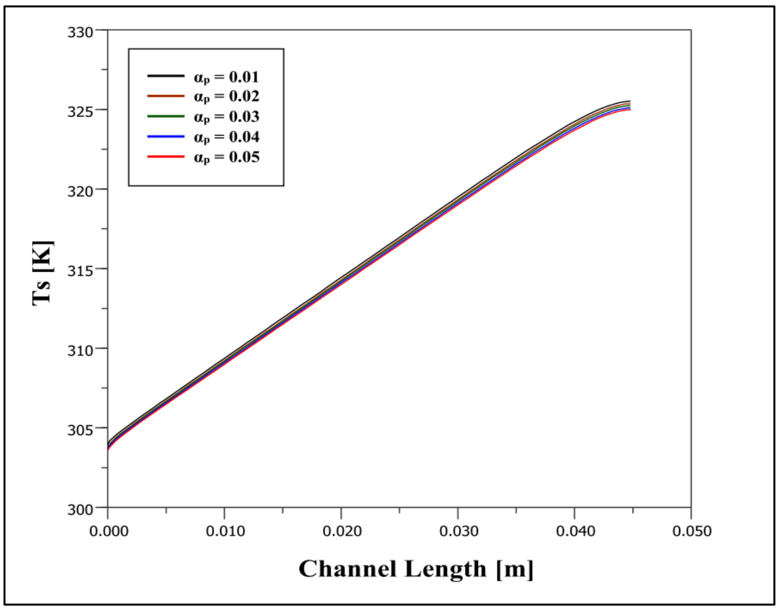

Figure 16. Comparison of substrate wall temperature with different particle concentration

Fig 17 presents the effect of particle concentration on bulk fluid temperature. The effect of particle concentration on bulk fluid temperature is as same as the effect on surface temperature. As a consequence, bulk fluid temperature decreases. With concentration increasing, bulk fluid temperature decreases with decreasing specific heat and increasing conductivity. The reduced amplitude is enlarged with volume fraction increasing although the variation is trivial due to the micro-channel heat sink's small-scale size.

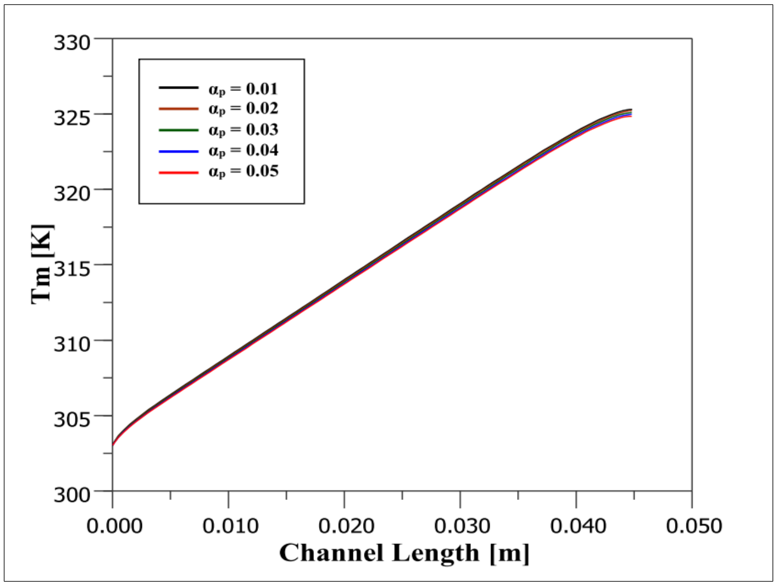

Figure 17. Comparison of fluid mean temperature with different particle concentrations

So, from our study, it has been found that the effect of particle concentration increment on the enhancement heat transfer coefficient is recognizable. But the effect of concentration increment on bulk fluid and channel surface temperature is very mini-scale and unnoticeable due to miniature size and compactness of microchannel heatsink. These findings prove that although with concentration increasing, the heat transfer coefficient increases rapidly but due to the compactness of the heat sink, temperature variation is negligible; hence the cooling effectiveness is indistinguishable.

4.3.4 Performance Evaluation Criterion

Performance evaluation criteria (PEC) has been introduced to assess the overall performance of particle's concentration variation. Figure 16 shows the variation of PEC with Reynolds number and nanoparticles volume fraction.

It has been found that, with the increase of Reynolds number, the PEC decreases. This changing tendency shows that the energetic cost of pumping power is much higher than the corresponding heat transfer enhancement benefit. (Zhou *et al.*, 2018) also agrees with this phenomena regarding the reduction of PEC with Reynolds number increases. The reduced amplitude of PEC varies for different concentration. It has been found for lower α_p; the PEC curve is much steeper. Which indicates overall thermal performance reduction considering pumping cost increment is larger for lower concentration with Reynolds number increasing.

It is also evident from the figure that for higher Reynolds number the influence of concentration on the thermal, hydraulic and overall performance is indistinguishable.

Fig 18 shows the effect of concentration on PEC for a fixed Re=500. The increment of concentration results in a reduction of PEC. Which indicates the energetic cost of pumping power is much higher than the corresponding heat transfer enhancement benefit for a higher concentration.

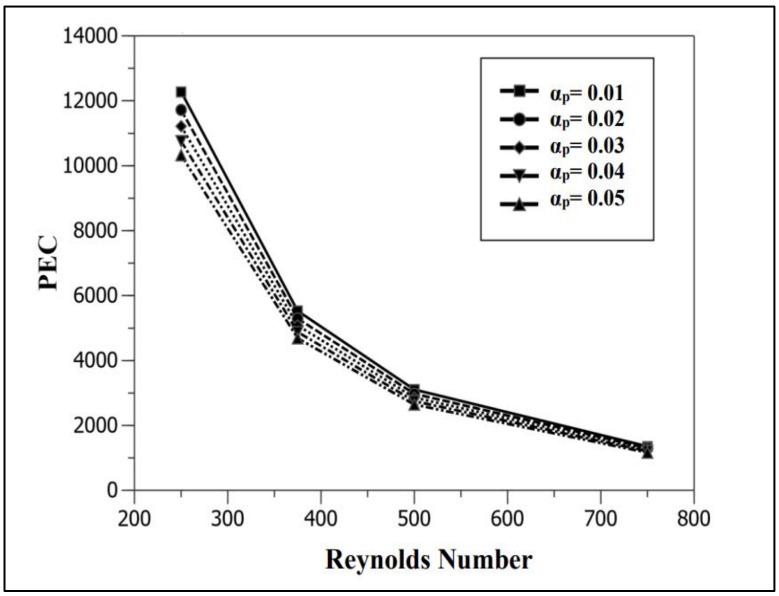

Figure 18. Comparison of PEC with different volume fraction of Nano fluids

Chapter 05: Conclusion and Recommendation

This section presents a summary of the findings from our proposed microchannel heat sink cooling technology. It is also extended to describe our study's limitations to pave the way for a detailed analysis with a vast scope in the near future.

5.1 Findings

Our study introduced the incorporation of Nano-liquid metal fluid as the cooling medium in MCHS. This serves as a state-of-the-art technology regarding the cooling solution for miniature electronic component. Our study has tried to contribute to this field with a detailed performance comparison of different conventionally used liquid metal and nanoparticle combinations. The findings of our study can be stated as following:

- GaIn based Nano liquid metal fluids displays the best thermal performance. For the same nanoparticle Al_2O_3 and Re=600, α_p =0.02 , GaIn based Nano fluids displays 3.41 times higher heat transfer coefficient than conventional Water-Al_2O_3 Nano fluid. Also, increasing Reynolds number from 300-600 results in a 131.58% heat transfer coefficient for GaIn based Nano fluids, where the same increment in Reynolds number results in only 31.23% increase of the heat transfer coefficient for water-based Nano fluids.
- Considering the hydraulic performance Ga based Nano fluids requires the least pumping power for the same Reynolds number. For Re=500 and α_p =0.02, EGaInSn based Nano fluids require 55% more pumping power than water, although Ga based Nano fluids require 11% less pumping power.
- Comparing the overall performance, Ga based Nano fluids are suitable considering energy efficiency. But regarding thermal performance, GaIn based Nano fluids are most appropriate.
- CNT particle-based Nano fluids display better thermal performance than conventional nanoparticles due to their high thermal conductivity. For GaIn as base fluid and Re=750, CNT particle has an enhancement of 12.48%, 9.48%, 8.79% over Al_2O_3, Cu, and Diamond particle.
- So, it's determined that the GaIn-CNT mixture exhibits the highest thermal performance. For the same Reynolds number, the GaIn-CNT mixture has a heat transfer coefficient

increment of 2.68%, 17.19%, 22.16%, 2.62% over CNT particle-based EGaIn EGaInSn, Ga, GaSn liquid metal, respectively.

- With particle concentration increasing, heat transfer coefficient and pressure drop across the channel both increases due to mixture’s thermal conductivity and viscosity increase respectively. Although the increment is nonlinear and the rate of increment decreases with concentration increase.
- The effect of concentration increment on thermal and hydraulic performance with the variation of Reynolds number is negligible
- Despite their ability to enhance the single-phase heat transfer coefficient due to the increased thermal conductivity, the overall cooling effectiveness of particle concentration increment is relatively minuscule.
- Considering overall performance, increasing concentration results in a reduction of PEC which indicates the energetic cost of pumping power is much higher than the corresponding heat transfer enhancement benefit. And for higher Reynolds number the influence of concentration on the thermal, hydraulic and overall performance is indistinguishable.

5.2 Limitations

As our whole study is numerical simulation based, despite having good consistency and accuracy with reference experimental data (Lee and Mudawar, 2007), we have several limitations and constraints. It is suggested that as liquid metal has large surface tension, a much larger volume fraction of nanoparticles can be added to the liquid metal (Zhou *et al.*, 2018). Still the preparation and implementation of nano liqud metal fluid in such small scale application has not been carried out experimentally. Thus the feasibility and tangibility of the proposed cooling technology in MCHS is uncertain. But our study has tried to contribute in this field by providing a detailed comparative study of the characteristics of different nanofluid combinations and optimal range for cooling. The limitations of our numerical model are discussed below:

- There is no universal model for the determination of nanofluid mixture properties. Implementation of each model depends on the combination and context of the problem.
- Due to small scale heat transfer phenomena, it is very challenging to calculate the fin efficiency accurately.
- Prediction of the flow field and heat transfer phenomena for high velocity flow and high source heat flux is very challenging and intangible.
- High surface area to volume ratio of nanoparticles provides a very high surface energy. To minimize its surface energy, the nanoparticles, create agglomeration. Uncontrolled agglomeration of nanoparticles occurs due to attractive van der Waals forces between the particles. The physical phenomena of agglomeration have a disrupted effect on the overall performance of the sink by creating a huge disturbance in the flow field of MCHS. This phenomenon is uncontrolled and impossible to predict in numerical solution. Sonicating or adding surfactant might help for a short period of time but it will not helpful for long period because it’s going to aggregate again.

5.3 Future Recommendation

Ga and its alloys possess the ability to create metallic compounds of different morphologies, compositions, and properties, thereby enabling control over nanoscale phenomena. Interestingly, liquid metals have enormous surface tensions, yet the tension can be tuned electrically over a wide range or modified via surface species, such as the native oxides. The ability to control the interfacial tension allows these liquids to be readily reduced in size to the nanoscale. These properties pave the way to use liquid metals as base fluid for Nano fluid combinations.

We compared the performance of Nano-liquid metal fluid combinations and achieved the optimal combination in different perspectives. We also found out the optimal range of Reynolds number and concentration for better and significant thermal performance. This built the foundation of future experimental work regarding the use of Nano liquid metal fluid in electronic component cooling. This technology is constrained by the expense of the preparation of nano-liquid metal fluids. But it is an inception regarding the solution of bottleneck cooling issues associated with miniaturization of electronic components.

Reference

Akbari, M., Galanis, N. and Behzadmehr, A. (2011) 'Comparative analysis of single and two-phase models for CFD studies of nanofluid heat transfer', *International Journal of Thermal Sciences*, 50(8), pp. 1343–1354. doi: 10.1016/j.ijthermalsci.2011.03.008.

Akbari, M., Galanis, N. and Behzadmehr, A. (2012) 'Comparative assessment of single and two-phase models for numerical studies of nanofluid turbulent forced convection', *International Journal of Heat and Fluid Flow*, 37, pp. 136–146. doi: 10.1016/j.ijheatfluidflow.2012.05.005.

Alfaryjat, A. *et al.* (2018) 'The impact of different base nanofluids on the fluid flow and heat transfer characteristics in rhombus microchannels heat sink', *UPB Scientific Bulletin, Series D: Mechanical Engineering*, 80(1), pp. 181–194.

Alfaryjat, A. *et al.* (2019) 'Experimental investigation of thermal and pressure performance in computer cooling systems using different types of nanofluids', *Nanomaterials*, 9(9). doi: 10.3390/nano9091231.

Ali, R., Palm, B. and Maqbool, M. H. (2012) 'Flow boiling heat transfer of refrigerants R134A and R245fA in a horizontal micro-channel', *Experimental Heat Transfer*, 25(3), pp. 181–196. doi: 10.1080/08916152.2011.609962.

Arshad, W. and Ali, H. M. (2017) 'Experimental investigation of heat transfer and pressure drop in a straight minichannel heat sink using TiO2 nanofluid', *International Journal of Heat and Mass Transfer*, 110, pp. 248–256. doi: 10.1016/j.ijheatmasstransfer.2017.03.032.

Azizi, Z., Alamdari, A. and Malayeri, M. R. (2015) 'Convective heat transfer of Cu-water nanofluid in a cylindrical microchannel heat sink', *Energy Conversion and Management*, 101, pp. 515–524. doi: 10.1016/j.enconman.2015.05.073.

Azizi, Z., Alamdari, A. and Malayeri, M. R. (2016) 'Thermal performance and friction factor of a cylindrical microchannel heat sink cooled by Cu-water nanofluid', *Applied Thermal Engineering*, 99, pp. 970–978. doi: 10.1016/j.applthermaleng.2016.01.140.

Bahiraei, M. and Heshmatian, S. (2018) 'Thermal performance and second law characteristics of two new microchannel heat sinks operated with hybrid nanofluid containing graphene-silver nanoparticles', *Energy Conversion and Management*, 168(December 2017), pp. 357–370. doi:

10.1016/j.enconman.2018.05.020.

Balaji, T. *et al.* (2020) 'Enhanced heat transport behavior of micro channel heat sink with graphene based nanofluids', *International Communications in Heat and Mass Transfer*, 117, p. 104716. doi: 10.1016/j.icheatmasstransfer.2020.104716.

Barbier, F. and Blanc, J. (1999) 'Corrosion of martensitic and austenitic steels in liquid gallium', *Journal of Materials Research*, 14(3), pp. 737–744. doi: 10.1557/JMR.1999.0099.

Chandra, S. and Prakash, O. (2016) 'Heat Transfer in Microchannel Heat Sink: Review', *International Conference on Recent Advances in Mechanical Engineering*, (October 2016).

Choi, S. U. S. (2009) 'Nanofluids: From vision to reality through research', *Journal of Heat Transfer*, 131(3), pp. 1–9. doi: 10.1115/1.3056479.

Deng, Y. G. and Liu, J. (2009) 'Corrosion development between liquid gallium and four typical metal substrates used in chip cooling device', *Applied Physics A: Materials Science and Processing*, 95(3), pp. 907–915. doi: 10.1007/s00339-009-5098-1.

Dong, T. *et al.* (2008) 'Freon R141b flow boiling in silicon microchannel heat sinks: Experimental investigation', *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, 44(3), pp. 315–324. doi: 10.1007/s00231-007-0236-9.

El-Batsh, H. M., Doheim, M. A. and Hassan, A. F. (2012) 'On the application of mixture model for two-phase flow induced corrosion in a complex pipeline configuration', *Applied Mathematical Modelling*, 36(11), pp. 5686–5699. doi: 10.1016/j.apm.2012.01.017.

Farajollahi, B., Etemad, S. G. and Hojjat, M. (2010) 'Heat transfer of nanofluids in a shell and tube heat exchanger', *International Journal of Heat and Mass Transfer*, 53(1–3), pp. 12–17. doi: 10.1016/j.ijheatmasstransfer.2009.10.019.

Gong, L., Zhao, J. and Huang, S. (2015) 'Numerical study on layout of micro-channel heat sink for thermal management of electronic devices', *Applied Thermal Engineering*, 88, pp. 480–490. doi: 10.1016/j.applthermaleng.2014.09.048.

Hadad, Y. *et al.* (2019) 'Three-objective shape optimization and parametric study of a micro-channel heat sink with discrete non-uniform heat flux boundary conditions', *Applied Thermal*

Engineering, 150(January), pp. 720–737. doi: 10.1016/j.applthermaleng.2018.12.128.

Halelfadl, S. *et al.* (2014) 'Optimization of thermal performances and pressure drop of rectangular microchannel heat sink using aqueous carbon nanotubes based nanofluid', *Applied Thermal Engineering*, 62(2), pp. 492–499. doi: 10.1016/j.applthermaleng.2013.08.005.

Han, Y. *et al.* (2012) 'A review of development of micro-channel heat exchanger applied in air-conditioning system', *Energy Procedia*, 14, pp. 148–153. doi: 10.1016/j.egypro.2011.12.910.

Hatami, M. and Ganji, D. D. (2014) 'Thermal and flow analysis of microchannel heat sink (MCHS) cooled by Cu-water nanofluid using porous media approach and least square method', *Energy Conversion and Management*, 78, pp. 347–358. doi: 10.1016/j.enconman.2013.10.063.

Ho, C. J., Wei, L. C. and Li, Z. W. (2010) 'An experimental investigation of forced convective cooling performance of a microchannel heat sink with Al2O3/water nanofluid', *Applied Thermal Engineering*, 30(2–3), pp. 96–103. doi: 10.1016/j.applthermaleng.2009.07.003.

Huminic, G. and Huminic, A. (2012) 'Application of nanofluids in heat exchangers: A review', *Renewable and Sustainable Energy Reviews*, 16(8), pp. 5625–5638. doi: 10.1016/j.rser.2012.05.023.

In, S. and Jeong, S. (2009) 'Flow boiling heat transfer characteristics of R123 and R134a in a micro-channel', *International Journal of Multiphase Flow*, 35(11), pp. 987–1000. doi: 10.1016/j.ijmultiphaseflow.2009.07.003.

Jang, S. P. and Choi, S. U. S. (2006) 'Cooling performance of a microchannel heat sink with nanofluids', *Applied Thermal Engineering*, 26(17–18), pp. 2457–2463. doi: 10.1016/j.applthermaleng.2006.02.036.

Japar, W. M. A. A. *et al.* (2018) 'A comprehensive review on numerical and experimental study of nanofluid performance in microchannel heatsink (MCHS)', *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 45(1), pp. 165–176.

Kalteh, M. *et al.* (2012) 'Experimental and numerical investigation of nanofluid forced convection inside a wide microchannel heat sink', *Applied Thermal Engineering*, 36(1), pp. 260–268. doi: 10.1016/j.applthermaleng.2011.10.023.

Kandlikar, S. G. (2007) 'A roadmap for implementing minichannels in refrigeration and air-conditioning systems - Current status and future directions', *Heat Transfer Engineering*, 28(12), pp. 973–985. doi: 10.1080/01457630701483497.

Keshavarz Moraveji, M. and Hejazian, M. (2012) 'Modeling of turbulent forced convective heat transfer and friction factor in a tube for Fe 3o 4 magnetic nanofluid with computational fluid dynamics', *International Communications in Heat and Mass Transfer*, 39(8), pp. 1293–1296. doi: 10.1016/j.icheatmasstransfer.2012.07.003.

Khanafer, K., Vafai, K. and Lightstone, M. (2003) 'Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids', *International Journal of Heat and Mass Transfer*, 46(19), pp. 3639–3653. doi: 10.1016/S0017-9310(03)00156-X.

Kim, S. J. *et al.* (2007) 'Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux', *International Journal of Heat and Mass Transfer*, 50(19–20), pp. 4105–4116. doi: 10.1016/j.ijheatmasstransfer.2007.02.002.

Kulkarni, D. P., Das, D. K. and Vajjha, R. S. (2009) 'Application of nanofluids in heating buildings and reducing pollution', *Applied Energy*, 86(12), pp. 2566–2573. doi: 10.1016/j.apenergy.2009.03.021.

Kumar, V. and Sarkar, J. (2020) 'Particle ratio optimization of Al2O3-MWCNT hybrid nanofluid in minichannel heat sink for best hydrothermal performance', *Applied Thermal Engineering*, 165(August 2019), p. 114546. doi: 10.1016/j.applthermaleng.2019.114546.

Lee, J. and Mudawar, I. (2007) 'Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels', *International Journal of Heat and Mass Transfer*, 50(3–4), pp. 452–463. doi: 10.1016/j.ijheatmasstransfer.2006.08.001.

Li, X. and Jia, L. (2015) 'The investigation on flow boiling heat transfer of R134a in micro-channels', *Journal of Thermal Science*, 24(5), pp. 452–462. doi: 10.1007/s11630-015-0808-9.

Liu, H. L., An, X. K. and Wang, C. S. (2017) 'Heat transfer performance of T-Y type micro-channel heat sink with liquid GaInSn coolant', *International Journal of Thermal Sciences*, 120, pp. 203–219. doi: 10.1016/j.ijthermalsci.2017.06.008.

Liu, Y. *et al.* (2015) 'Heat transfer performance of lotus-type porous copper heat sink with liquid

GaInSn coolant', *International Journal of Heat and Mass Transfer*, 80, pp. 605–613. doi: 10.1016/j.ijheatmasstransfer.2014.09.058.

Liu, Z. H. and Li, Y. Y. (2012) 'A new frontier of nanofluid research - Application of nanofluids in heat pipes', *International Journal of Heat and Mass Transfer*, 55(23–24), pp. 6786–6797. doi: 10.1016/j.ijheatmasstransfer.2012.06.086.

Lotfi, R., Rashidi, A. M. and Amrollahi, A. (2012) 'Experimental study on the heat transfer enhancement of MWNT-water nanofluid in a shell and tube heat exchanger', *International Communications in Heat and Mass Transfer*, 39(1), pp. 108–111. doi: 10.1016/j.icheatmasstransfer.2011.10.002.

Ma, K. Q. and Liu, J. (2007) 'Nano liquid-metal fluid as ultimate coolant', *Physics Letters, Section A: General, Atomic and Solid State Physics*, 361(3), pp. 252–256. doi: 10.1016/j.physleta.2006.09.041.

Mansour, R. Ben, Galanis, N. and Nguyen, C. T. (2007) 'Effect of uncertainties in physical properties on forced convection heat transfer with nanofluids', *Applied Thermal Engineering*, 27(1), pp. 240–249. doi: 10.1016/j.applthermaleng.2006.04.011.

Maré, T. *et al.* (2011) 'Comparison of the thermal performances of two nanofluids at low temperature in a plate heat exchanger', *Experimental Thermal and Fluid Science*, 35(8), pp. 1535–1543. doi: 10.1016/j.expthermflusci.2011.07.004.

Martínez, V. A. *et al.* (2019) 'Numerical study of TiO2-based nanofluids flow in microchannel heat sinks: Effect of the Reynolds number and the microchannel height', *Applied Thermal Engineering*, 161(July). doi: 10.1016/j.applthermaleng.2019.114130.

Masuda, H. *et al.* (1993) 'Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles. Dispersion of Al2O3, SiO2 and TiO2 Ultra-Fine Particles.', *Netsu Bussei*, 7(4), pp. 227–233. doi: 10.2963/jjtp.7.227.

Mohd-Ghazali, N. *et al.* (2019) 'Thermal and hydrodynamic performance of a microchannel heat sink with carbon nanotube nanofluids: Effect of concentration and channel section', *Journal of Thermal Analysis and Calorimetry*, 138(2), pp. 937–945. doi: 10.1007/s10973-019-08260-2.

Mokhtari Moghari, R. *et al.* (2011) 'Two phase mixed convection Al2O3-water nanofluid flow in an annulus', *International Journal of Multiphase Flow*, 37(6), pp. 585–595. doi: 10.1016/j.ijmultiphaseflow.2011.03.008.

Moraveji, M. K. *et al.* (2011) 'Modeling of convective heat transfer of a nanofluid in the developing region of tube flow with computational fluid dynamics', *International Communications in Heat and Mass Transfer*, 38(9), pp. 1291–1295. doi: 10.1016/j.icheatmasstransfer.2011.06.011.

Moraveji, M. K. and Ardehali, R. M. (2013) 'CFD modeling (comparing single and two-phase approaches) on thermal performance of Al2o3/water nanofluid in mini-channel heat sink', *International Communications in Heat and Mass Transfer*, 44, pp. 157–164. doi: 10.1016/j.icheatmasstransfer.2013.02.012.

Muhammad, A. *et al.* (2020) 'Comparison of pressure drop and heat transfer performance for liquid metal cooled mini-channel with different coolants and heat sink materials', *Journal of Thermal Analysis and Calorimetry*, 141(1), pp. 289–300. doi: 10.1007/s10973-020-09318-2.

Muhammad, A., Selvakumar, D. and Wu, J. (2020) 'Numerical investigation of laminar flow and heat transfer in a liquid metal cooled mini-channel heat sink', *International Journal of Heat and Mass Transfer*, 150, p. 119265. doi: 10.1016/j.ijheatmasstransfer.2019.119265.

Mukesh Kumar, P. C. and Arun Kumar, C. M. (2020) 'Numerical study on heat transfer performance using Al2O3/water nanofluids in six circular channel heat sink for electronic chip', *Materials Today: Proceedings*, 21(xxxx), pp. 194–201. doi: 10.1016/j.matpr.2019.04.220.

Mukherjee, S. *et al.* (2018) 'Theoretical modeling and optimization of microchannel heat sink cooling with TiO2-water and ZnO-water nanofluids', *International Journal of Heat and Technology*, 36(1), pp. 165–172. doi: 10.18280/ijht.360122.

Naqiuddin, N. H. *et al.* (2018) 'Numerical investigation for optimizing segmented micro-channel heat sink by Taguchi-Grey method', *Applied Energy*, 222(December 2017), pp. 437–450. doi: 10.1016/j.apenergy.2018.03.186.

Nitiapiruk, P. *et al.* (2013) 'Performance characteristics of a microchannel heat sink using TiO2/water nanofluid and different thermophysical models', *International Communications in Heat and Mass Transfer*, 47, pp. 98–104. doi: 10.1016/j.icheatmasstransfer.2013.07.001.

Pantzali, M. N. *et al.* (2009) ‘Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface’, *International Journal of Heat and Fluid Flow*, 30(4), pp. 691–699. doi: 10.1016/j.ijheatfluidflow.2009.02.005.

Popescu, T. *et al.* (2012) ‘Microchannel heat exchangers - Present and perspectives’, *UPB Scientific Bulletin, Series D: Mechanical Engineering*, 74(3), pp. 55–70.

Qi, C. *et al.* (2017) ‘Two-phase lattice Boltzmann simulation of the effects of base fluid and nanoparticle size on natural convection heat transfer of nanofluid’, *International Journal of Heat and Mass Transfer*, 105, pp. 664–672. doi: 10.1016/j.ijheatmasstransfer.2016.10.043.

Qi, C., Liang, L. and Rao, Z. (2016) ‘Study on the flow and heat transfer of liquid metal based nanofluid with different nanoparticle radiuses using two-phase lattice Boltzmann method’, *International Journal of Heat and Mass Transfer*, 94, pp. 316–326. doi: 10.1016/j.ijheatmasstransfer.2015.11.068.

Razali, A. A., Sadikin, A. and Ibrahim, S. A. (2017) ‘Heat transfer of Al2O3 nanofluids in microchannel heat sink’, *AIP Conference Proceedings*, 1831. doi: 10.1063/1.4981191.

Saripella, S. K. *et al.* (2007) ‘Effects of nanofluid coolant in a class 8 truck engine’, *SAE Technical Papers*, (724). doi: 10.4271/2007-01-2141.

Sawada, T. *et al.* (2000) ‘Gallium-cooled liquid metallic-fueled fast reactor’, *Progress in Nuclear Energy*, 37(1–4), pp. 313–319. doi: 10.1016/s0149-1970(00)00064-0.

Sidik, N. A. C., Yazid, M. N. A. W. M. and Mamat, R. (2015) ‘A review on the application of nanofluids in vehicle engine cooling system’, *International Communications in Heat and Mass Transfer*, 68, pp. 85–90. doi: 10.1016/j.icheatmasstransfer.2015.08.017.

Sivakumar, A., Alagumurthi, N. and Senthilvelan, T. (2017) ‘Effect of Serpentine Grooves on Heat Transfer Characteristics of Microchannel Heat Sink with Different Nanofluids’, *Heat Transfer - Asian Research*, 46(3), pp. 201–217. doi: 10.1002/htj.21206.

Smither, R. K. *et al.* (1988) ‘Liquid gallium metal cooling for optical elements with high heat loads’, *Nuclear Inst. and Methods in Physics Research, A*, 266(1–3), pp. 517–524. doi: 10.1016/0168-9002(88)90440-8.

Song, H. *et al.* (2020) 'Ga-Based Liquid Metal Micro/Nanoparticles: Recent Advances and Applications', *Small*, 16(12), pp. 1–21. doi: 10.1002/smll.201903391.

Tawk, M. *et al.* (2013) 'Numerical and experimental investigations of the thermal management of power electronics with liquid metal mini-channel coolers', *IEEE Transactions on Industry Applications*, 49(3), pp. 1421–1429. doi: 10.1109/TIA.2013.2252132.

Taylor, P. (2006) 'Advances in science and technology of compact heat exchangers', *Heat Transfer Engineering*, 27(5), pp. 3–22. doi: 10.1080/01457630600559462.

Tuckerman, D. B. *et al.* (1981) 'High-performance heat sinking for VLSI', *IEEE Electron Device Letters*, 2(5), pp. 126–129. doi: 10.1109/EDL.1981.25367.

Vasu, V., Rama Krishna, K. and Kumar, A. C. S. (2008) 'Thermal design analysis of compact heat exchanger using nanofluids', *International Journal of Nanomanufacturing*, 2(3), pp. 271–288. doi: 10.1504/IJNM.2008.018949.

Weisberg, A., Bau, H. H. and Zemel, J. N. (1992) 'Analysis of microchannels for integrated cooling', *International Journal of Heat and Mass Transfer*, 35(10), pp. 2465–2474. doi: 10.1016/0017-9310(92)90089-B.

Wen, D. and Ding, Y. (2004) 'Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions', *International Journal of Heat and Mass Transfer*, 47(24), pp. 5181–5188. doi: 10.1016/J.IJHEATMASSTRANSFER.2004.07.012.

Zhou, X. *et al.* (2018) 'Numerical study of heat transfer enhancement of nano liquid-metal fluid forced convection in circular tube', *Journal of Heat Transfer*, 140(8). doi: 10.1115/1.4039685.